Petroleum Geomechanics

(Introduction to Rock Mechanics in Petroleum Engineering)

Maurice Dusseault
Petroleum Exploration & Production

- Geosciences
  - Geology
  - Geophysics
- Diffusion Sciences (Transport)
  - Darcy – fluid flow = $f(\Delta p, \text{permeability}…)$
  - Thermal – heat flow = $f(\Delta T, \text{conductivity}…)$
  - Fickian – ionic flow = $f(\Delta C, \text{diffusivity}…)$
- Thermodynamics (energy, phase behavior, etc.)
- Geomechanics
  - Geomechanics is often secondary, but not always!
Heavy Oil Production…

Production Processes

Primary
- Cold Production
- CHOPS

Thermal
- Steam
  - CSS
  - Flooding
  - SAGD
- Combustion
  - Fire Flooding
  - THAI™
  - Top Down

Non-Thermal
- Water Flooding, ASP
- CO₂, Gas Inj.
- Chemical Inj.
- VAPEX

Hybrid Processes

Anoxic Pyrolysis

Sequencing
Importance of Geomechanics

- What is **GEOMECHANICS**?
  - Geo + mechanics: Mechanics of geological materials (soils, rocks, fluids in the rocks…)
  - …deformation-yield-flow behavior of geomaterials exposed to changes in stresses, pressures, temperatures and chemistry.
  - …used in exploration, drilling, reservoir eng., completion, waste disposal, pipelines…
- Geomechanics applications are growing…
- Geomechanics knowledge helps **reduce risk**
Stress and Pressure

- Petroleum geomechanics deals with stress & pressure
- Stress is a force over an area
- Pressure is that part of the boundary forces supported by the fluid phase only
- Do not confuse the two! Pressure – \( p \) – used for fluids only.
- Fluid can be water, oil, gas…

\[
\sigma_a = \frac{F_a}{A}
\]
Geomechanics and Oil...

\[ \Delta \sigma' - \text{stress changes} \]
\[ \Delta p - \text{pressure changes} \]
\[ \Delta C - \text{chemistry changes} \]
\[ \Delta T - \text{temperature changes} \]
\[ = \Delta V - \text{volume changes} \]
Example: Thermal Contraction...

- What happen if you severely cool the rock? (i.e.: $-\Delta T$)
- Shrinking (i.e.: $-\Delta V$)
- Loss of confining stress (i.e.: $-\Delta \sigma'$)
- Loss of frictional strength
- The rock slips…

$\Delta \sigma' - \Delta T = -\Delta V$
Shale Barriers and SAGD

Shales are impermeable to steam, and behave differently than sands

SAGD passes through thin shales ($\Delta V/\Delta T$ & $t$ effects)

Shales 1 m thick can be passed: thermal geomechanics effects
Surface heaves cannot be explained by $\Delta T$ & $\Delta p$ alone: there must be shear dilation taking place. Therefore, there are massive changes in the reservoir properties – $k$, $C_c$, $\phi$,
Geomechanics Applications

- Exploration issues: geology, geophysics, oil emplacement, abnormal pressures, ...
- Drilling engineering, borehole stability, casing placement, mud weight window...
- Completions engineering, fracturing
- Reservoir engineering, compaction, fluid flow, thermal stresses, ...
- Process monitoring and optimization...
- Storage and transportation of products...
- Environmental issues, waste disposal, CO$_2$ sequestration (see next slide...)
Carbon Dioxide Emissions...

Sequestration involves geomechanics at all stages...

Recovered CO₂ Injection

EOR

Sequestration: EOR, Δp, Δσ′, ΔC...

Carbon emissions (tonnes C/TJ)

Environment Canada
Geomechanics and the Value Chain...

- Some of geomechanics is problem avoidance and risk reduction: for example, in drilling...
  - Stress determination in the earth with depth helps choose the maximum MW and casing points
  - Pressure determination and borehole stability analysis help set the minimum MW and casing points
- Geomechanics also saves $ (increased value)
  - Underbalanced drilling (reduced time and damage)
- …and helps find resources…
  - Stress history and pressure valving in basins
1. Underbalanced drilling requires rock strong enough to remain open under the additional forces from fluid influx.

2. UB drilling is much faster: time-dependent strength losses in shale are low.

3. Fluid flux is inward, thus shale strength is not affected by mud filtrate.

4. Formation damage reduced (e.g. capillary blockage), giving better production.

*Damage to the reservoir during overbalanced drilling results from the influx of non-native fluids, chemicals and formation solids into the porosity of the formation.*

*Drilling Contractor, Jul/Aug 2003*
Geomechanics and Exploration

- State of stress in the earth (drilling, fractures)
- Sedimentary basin types and stress distributions (finding oil accumulations)
- Inference of rock properties from seismics and geophysical logs (reservoir analysis)
- Structural and lithostratigraphic issues
- Hydraulic valving of reservoirs (finding gas, predicting pressures in reservoirs)
- Abnormally pressured zones…
Stresses Above a Domal Structure

Fault identification can help well planning (avoidance)

Dry Hole

Oil Well

Normal faulting

\( \sigma_v > \sigma_h \)

Seismic reflection time

Migrated seismic section through an oil field
Drilling Geomechanics

- Bit-rock interaction
- Stresses and pressures around a borehole
- Physical behavior of shales in vertical and deviated wells
- Borehole stability analysis
- Formation damage
- Diffusion processes ($\Delta T$, $\Delta p$, $\Delta C$)
- Salt squeeze and viscous rock behavior
- Disposal of drill cuttings by annular injection
Horizontal, Slant Wellbore Stability

Vertical stress - $\sigma_v$

Earth stresses

Bit-rock processes

Courtesy Statoil
Completions Geomechanics

- Mechanical aspects of formation damage
- Stresses during and after cementing casing
- Perforating the cased hole (see next slide)
- Hydraulic fracture geomechanics
  - Why fractures rise and where they go
  - Frac-and-pack strategies for completions
  - Staged fracturing of long horizontal well
  - Stresses and fracture direction control
  - Fracturing naturally fractured reservoirs (see example at end of this module)
**Perforation-Damaged Zones**

- **Drilling damage** = weakened rock
- Cement is broken, permeable
- Perforation damage

Geomechanics issues...

- Cohesion damage
- Introduction of a “flaw”
- Focusing of flow paths
Hydraulic Fracture, Microseismics

- Barnett Shale gas play, Dallas-Ft. Worth region, HF necessary
- Naturally fractured shaley reservoir, low matrix permeability
- Single or multiple HF fractures??
- This microseismic-Δt trace shows:
  - Growth of fracture length
  - Opening of “associated” natural fractures in the Barnett reservoir
  - Much larger drainage area!

What is poroelasticity?

- Compaction and subsidence (Maracaibo, Wilmington, Ekofisk, Ravenna, Groeningen…)

- Induced seismicity during conventional reservoir exploitation ($\Delta p$ processes)

- Geomechanics & thermal EOR processes ($\Delta T$)
  - Thermal stresses in reservoirs
  - Changes in rock properties during EOR (dilation)
  - Changes in stresses, induced seismicity
  - Casing shear problems
SAGD and Geomechanics...

Cap Rock

Steam Chambers

Unrecovered heavy oil

Caprock integrity

Producer well

Injector well

Well integrity

Steam rises and heats bitumen

Oil & Water

Slotted liner loads

Sand dilation and changes in properties

Wilmington, California

- Bowl shaped $\Delta z$
- Shear of casings occurred mainly on the shoulders of the subsidence bowl
- Few shears in the middle, where $\Delta z$ greatest
- Few on flanks
- Associated earthquakes
Reservoir Engineering (II)

- Conventional sand production (avoidance)
- Sand management (production enhancement)
- Geomechanics of massive sanding as a production mechanism in heavy oils
- Geomechanics aspects of methane production from coal seams (see next slide)
- Production and injection stress changes
  - Changes in fractured rock permeability
  - Changes in fracture gradient because of production
- Waste disposal by slurry injection
Well 14-8 Performance

Luseland Field

Central Well 14 - 8

Production rate (bbl/d)

Oil rate

Start CHOPS

Water rate

Jan-81 Jan-85 Jan-89 Jan-93 Jan-97 Jan-01
Flow Path Development in CHOPS

Short flow path in low $k_v$ area, long flow path in high $k_h$ zone

Vertical exaggeration x10-20

Massive sand yield is the mechanism behind CHOPS
Late-Time Coalbed Permeability

1. The CH$_4$ is depleted near the wellbore, $-\Delta V$ in coal blocks.
2. Coal fractures open up, increasing permeability.
3. Closure stress drop, helping fractures remain open.
4. The well improves with time!
In HO unconsolidated sandstones, geomechanics behavior is a first-order factor…

- Thermal expansion and shear-induced dilation
- Recompauction drive in cyclic Δp processes (CSS)
- Shear of casing because of formation shear
- Integrity of overburden seal
- Changes in k, C_c, φ because of dilation

An understanding of the geomechanics issues involved in thermal EOR helps operations and planning…
Surface heaves cannot be explained by $\Delta T$ & $\Delta p$ alone: there must be shear dilation taking place. Therefore, there are massive changes in the reservoir properties – $k$, $C_c$, $\phi$, 

Surface heave – $\Delta z$ – above a SAGD project
Casing Shear

Reality

Simulation
Environmental Issues

- Petroleum development generates wastes…
  - Drilling wastes, OBM, spent chemicals…
  - Production wastes, sludges, tank bottoms, produced sand, spills, oily saline produced water, scale, etc.
  - Wastes during refining and upgrading of heavy oil include coke, sulfur (?), ash, sludges, etc.

- Waste treatment and disposal
  - Chemical or thermal treatment and landfiling…
  - Injection of liquids, gas scrubbing…
  - Slurry fracture injection for solids…
Permanent Disposal Options

Geological Disposal of Solid Wastes

- permanent warehousing
- landfills, quarries
- old or new mines
- ocean dumping
- deep solids slurry injection
- salt caverns

Remember: disposal means disposal; treatment often means new waste streams are generated, but yet must be disposed.
CHOPS Produced Sand in Canada

Heavy Oil is a “Dirty” Business
Emulsions

Oily Sand

Tank Bottoms

Pit Slops
Waste Disposal…

Slurry injection of sulfur is being considered in Alberta and Kazakhstan to dispose huge excess S volumes

Is S a waste? Is coke a waste? Do we store them indefinitely? How do we dispose or treat wastes cheaply, with high environmental security?
Solid Waste Injection Site - Duri
Process Monitoring

- PVT and geochemical data
- Well tests and geomechanics inference
- Deformation monitoring ($\Delta z$, $\Delta \theta$, $\Delta l$)
- Seismic monitoring (3D, X-hole, VSP)
- Microseismic monitoring
- Electrical monitoring
- Integrated reservoir monitoring for process understanding and management
Time-Lapse Seismics

Shell Peace River, horizontal well cyclic steam stimulation

Red areas = large drops in wave amplitude related to steam injection (Δsaturation, fabric dilation - ΔV, stress changes, pressure changes…)


\[
\frac{\Delta A}{\Delta t}
\]
The Next Challenge… NFR’s

- Naturally Fractured Carbonates! …and Shales!
- ~2 Tb heavy oil, 15% of world OOIP in NFCRs
- Huge amounts of shale gas - Montney, Horn River, Marcellus, Utica (Quebec)…
- Shale oil – Monterey (Cal.), Bakken …
- Multi-porosity systems
  - Fractures – Matrix – Vugs (dolomitization)
- We need to develop better understanding of fractures and geomechanics in NFR’s
- A geoscience and geomechanics challenge.
Different Joint Sets

Source: N. Barton and A. Makurat
The Next Challenge…

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<th>Depth</th>
<th>Core</th>
<th>Lithology</th>
<th>Penetration Type</th>
<th>Porosity (%)</th>
<th>Liquefaction</th>
<th>Oil Banishing</th>
<th>Dolomite</th>
<th>Rock and fossil assemblage</th>
<th>Sedimentary Structures</th>
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<td>dissolution</td>
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1-A Intro to Petroleum Geomechanics

Alberta Geological Survey
Rough or Smooth?
Lessons Learned...

- Geomechanics issues arise in almost all branches of the oil and gas E&P industry.
- Borehole stability, hydraulic fracturing, sand production, reservoir compaction, etc., are among issues dominated by geomechanics.
- Implementing geomechanics into planning saves money, avoids problems, reduces risk.
- Geomechanics issues are first-order effects in oil sands development, fracturing, CO$_2$ sequestration, solid waste disposal...