Some Geomechanics Issues in Petroleum Generation and Migration

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Some Geomechanics Issues

- Burial, $\phi$ loss (physicochemical diagenesis)
- Catagenesis $\rightarrow$ oil generation $\rightarrow$ then gas
- Expulsion of generated oil from shales
- Driving forces $\rightarrow$ pressure, gravity (buoyancy)
- Migration along faults, fractures
- Fracturing because of pressure build-up
  - Pressuring of shallow sands
- Generation of fractures in shale, other rocks, aperture and stress…
Porosity Loss with Depth = Energy

Porosity

Depth

0 0.25 0.50 0.75 1.0

sands & sandstones

clay & shale, “normal” line

Overpressure interval

4-6 km

Open fractures at depth

Stress and chemistry drive diagenesis

Porosity loss builds pressure = driving force

Can be retarded by high pressures, early oil migration
Porosity × Depth

- In a monotonically buried basin:
  - Porosity trends with depth are relatively consistent
  - Overpressured zones are important anomalies

- In an uplifted basin:
  - Porosities lower than “expected” - Michigan Bsn
  - Relationships are more complex

- In a compressional basin:
  - High stresses cause far more compaction
  - Compactive shearing can occur as well

- Region-dependent data are required
An Unconsolidated Sandstone

- St Peter Snds, (source of Ottawa Sand), $\phi = 26\%$
- Ordovician age, max Z perhaps 800-1000 m
- 99.5 SiO$_2$
- Highly rounded grains – aeolian/beach sand
- Indentations evidence of contact pressure solution
- No cement whatsoever
- High friction angles because of interlocking

This rock has lost 30% of its original porosity, $(35 - 26)/35$
Extreme Diagenesis Case

This rock has lost 90% of its original \( \phi \), expelling fluids.
Compaction Drive Energy...

- Shales are the source rocks...
- Sands, limestones are the reservoirs...
- Porosity loss is a major migration drive energy
- Deep burial, high $\sigma'$, $\phi$ loss, fluids expulsion
- These fluids migrate up-dip
- Faults and fractures as well
  - These features are stress-history related
- There are also buoyancy effects because oil and gas are lighter than water and are also immiscible...
Sandstone Diagenesis Evidence

- Dense grain packing
- Many long contacts
- Concavo-convex grain contacts
- $\text{SiO}_2$ precipitated in interstitial regions
- Only 1% solution at contacts = 8% loss in volume
- A stable interpenetrative fabric develops with high stiffness and strength

Fine-grained unconsolidated sandstone - Alberta Oil Sands
Burial compaction is also largely irreversible...
Hydrocarbon Migration

Seal: usually a shaley rock, salt, anhydrite

Hydrocarbon accumulation in the porous reservoir rock

Oil/water contact (OWC)

Migration route

Seal

Reservoir rock

Top of maturity

Source rock

High t, p

Rock mechanics, stresses, compaction... are vital factors in HC expulsion, migration, trapping, exploration, production
Microfissures generation - $\Delta p$, $\Delta T$, $\Delta \sigma = \Delta V$

- When $\sigma_3$ normal to fissures is $< p_o$
  - $p_o$ is the pressure in the shale pores
  - $\sigma_3$ is the stress at the scale of the microfissure

Various geological and tectonic processes:
  - Processes which increase $p_o$
  - Processes which change $\sigma_h$ ($\sigma_v \sim$ constant)
  - High temperatures dehydrate shales
  - Tectonic flexure of brittle rocks = joints
  - $-\Delta V$ leads to microfissures, joints, pathways
Can Water Flow Easily in Shale?

Much of the water in shales is not free to move easily:
- Adsorbed on the clay fragments
- Hydrated onto cations
- Pore throats are “blocked” by adsorbed water

Conclusion: even water cannot flow through intact shale!
Reduction in $\sigma_3$

- Tectonic unloading can reduce $\sigma_3$ ($\sigma_{\text{hmin}}$)
- Any shrinkage also reduces $\sigma_3$
  - *Clay compaction, thermal shrinkage
  - *Loading of anisotropic shales
  - *Smectite to mixed-layer to illite changes
- When $\sigma_3$ drops below $p_o$, fissures open
- Open fissures are dominantly vertical, very rarely horizontal (limited extent)
- Now, fluids can easily flow through the open cracks, migrate to traps & accumulate
Increase in p_o also Can Occur

- HC generation increases pore pressures
- Retarded compaction (overpressure)
- Smectite diagenesis releases H_2O
- Thermal pressuring increase p_o
- Accumulation of a thick gas zone in a reservoir with good vertical closure
- Tectonic loading (?) may increase p_o
- Other processes (e.g. gypsum dewatering)
- These processes (+Δz) give the driving forces for fluid flow and HC migration
Fluid Generation & Fracturing

Flow in shales must be through fractures!

- semi-solid organics, $p_o < \sigma_h < \sigma_v$
- high $T, p, \sigma$
- fractures develop and grow
- fluids are expelled through the fracture network, $p_o$ declines

3-20 mm

shale

kerogen

micro-fissure

fluid flow

ore and gas

generation of hydrocarbon fluids

$\sigma_v$

$T, p, \sigma$

increase

$\sigma_v$

$\sigma_v$

$\sigma_v$
Oil Expulsion from Shales...

- Organic shales are the source rocks for oil
- Below ~3500 m, at sufficient T... catagenesis
- Kerogen becomes liquid, $p \sim \sigma_v > \sigma_h$
- The oil is now at a pressure sufficient to generate microfissures
- The shale shrinks, further reducing $\sigma_h$
- Microfissures allow oil to escape the shale, flowing into permeable sands, carbonates
- Hence, sands, carbonates are the traps for expelled oil
Fluid migration is a function of stress as well as pressure!

This is called “valving” of gas.

- Hydraulic fracture occurs when \( p_o > \sigma_h \).
- Fault slips when \( \tau > (\sigma_n - p_o) \cdot \tan \phi' \), i.e., when \( \tau > \sigma'_n \cdot \tan \phi' \).

Stresses along A-A' effect:
- Gas cap, low density.
- Oil, density = 0.75-0.85.
As the Pressure Builds...

- Pressure builds from being fed by fluids and volume changes, plus gas-column effects
- Because the far-field stresses are roughly constant, an increasing pressure...
- Reduces the shear strength:
  \[ \tau_f = c' + \sigma'_n \cdot \tan(\phi') = c' + (\sigma_n - p) \cdot \tan(\phi') \]
  This tends to make faults slip!
- Also, increases the \( p_0 \) at the top of structures
  This leads to fracture generation when \( p_{\text{top}} > \sigma_{\text{hmin}} \)
Pressures at Depth

Hydrostatic pressure distribution: \( p(z) = \rho_w g z \)

Underpressured case:
underpressure ratio = \( p/(\rho_w g z) \), a value less than 1

Overpressured case:
overpressure ratio = \( p/(\rho_w g z) \), a value greater than 1.2

Normally pressured range:
\( 0.95 < p(\text{norm}) < 1.2 \)

Fresh water: \(~10\ \text{MPa/km}\)
Sat. NaCl brine: \(~12\ \text{MPa/km}\)
Flow and Basin Pressures

- Unbalanced pressures generate flow
  - Elevation effects (mountains – foreland basin)
  - Pressure maintained by compaction, by oil and gas generation, by mineral changes (e.g. gypsum, shales, etc.), and some other effects
  - Thermal effects as burial occurs, etc

- Density differences generate flow (oil-water)
  - Light oil is \(~0.825 (40°API)\), \(H_2O + NaCl \sim 1.05\)
  - Free gas (\(CH_4\)) is far lighter than \(H_2O\)
  - Upward, gravity-driven driving force
The Foreland Basin Model

Are Fractures Open or Closed?

Fractures in carbonates may be conduits as well.

Source: N. Barton and A. Makurat
Fracture Fabric and Stress Issues

- Fractures are major **conduits for migration**
- Fracture patterns also dictate **well layout**
- Is the cap rock a genuine seal for light phases (inert gas, steam, HC’s)? Are fractures open?
- What is the spatial variability of the fracture network *in situ*?
- Will a high T, p process lead to stress changes, altering fracture transmissivity? Will fracture dilation take place through shearing? Where?
- What about the tectonic fabric? Stresses?
Closure & Hysteresis

- What is the behavior of a joint under loading?
- Is the joint rough or smooth?
- How is the permeability changed?

Bandis - 1990
Fracture Compression, Nonlinearity

2-D Petroleum Generation and Migration

\[ \Delta \sigma'_n \]

\[ \text{asperities} \]

\[ \text{effective aperture} \]

\[ p \rightarrow p + \Delta p \]

\[ \Delta V \]

\[ \text{“soft”} \]

\[ \text{“stiff”} \]

\[ \text{Linear model} \]

\[ \sigma' \]

\[ \text{“soft”} \rightarrow \text{“stiff”} \]

\[ \text{Actual behavior} \]

\[ \text{effective stress - } \sigma'_n \]

\[ k' = f(a, \sigma') \]

\[ \text{fracture aperture - } a \]

\[ \text{fracture flow rate - } q \]

Strain and flow in fractured media are non-linear & stress-dependent
Are Joints Rough or Smooth?

Source: N. Barton and A. Makurat
Summary of Natural Fractures & $\Delta \sigma'$

- With a low-k matrix, fracture flow dominates
- Transmissivity is a strong function of the aperture: $q \propto a^2$ to $a^3$
- The aperture is sensitive to normal stress: if it goes up, aperture drops, flow rate drops
- Also, aperture can be changed by block rotation or shear of fractures surfaces:
  - Very complex area, little quantitative is known
  - May be vitally important in thermal processes in fractured carbonate rocks (large $\sigma'$ changes)
Summary

- Generation and migration of O&G are related to stresses as well as pressures and temperature.
- O&G must exit shales through fractures as shale is impermeable to different phases.
- Gas fracturing to surface can occur naturally, leading to drilling risks through shallow charged sands.
- Faults can be reactivated through our actions that change $T$, $p$, $V \rightarrow \Delta \sigma'_{ij}$: stress changes.
  - These issues are revisited later in the course…