Fractured Carbonates and Geomechanics Issues

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What are Carbonate Rocks?

- Made of a few minerals: Calcite and Dolomite (+ clays and auxiliary minerals)
- Carbonate rock-forming materials develop mainly through:
  - Biological activity that occurs in places with specific water T and other life-sustaining factors.
  - Inorganic precipitation, to a lesser degree
- 30% of sedimentary rocks
- >50% of conventional oil is in carbonates
- Fractures are sensitive to $\Delta \sigma'$!!
Carbonate Rocks: Distribution

- Canadian reefs
- North Sea Carbonates
- Permian Basin
- Mumbai Basin
- Persian Gulf and Zagros Fold Belt

Ahr et al, 2005
The vast Middle East conventional oil reserves are 95% in fractured carbonates.

There are ~2.2-2.5 Tb of viscous oil (>100 cP) in carbonates (mainly fractured).

- Zagros fold belt
- More flat-lying carbonates

Konert et al, 2001
ME Carbonate-Dominated Basins

- All these ME basins are CO$_3$– dominated
- Next in the world is probably the US Permian Basin (largely depleted)

Adopted from USGS, April 2007
Zagros Fold Belt, runs from the Straits of Hormuz up to eastern Turkey
Geomechanics Issues in Carbonates

- Very high porosity carbonates (such as North Sea Chalks) are collapsing rocks (see Section 5E).
- For the most part, carbonates, marls (carbonate-rich shales) are strong and relatively stiff, but...
- Fractured carbonates are the most common type, and these rocks are very stress-sensitive in their flow properties because of the fractures.
- Naturally Fractured Carbonate Reservoirs (NFCRs)
Here we see natural fractures in a limestone outcrop. Outcrop studies have been very important in building an understanding of carbonates...
Dual (or Triple) Porosity Media

- Matrix blocks, low k, usually 99% of the porosity, $\phi$ from 5-25%, stiff…
- Fractures, very high k, low proportion of the void space (~1%)
- This is called a dual-porosity medium… BUT!
- Carbonates that have been dolomitized or reefal carbonates have large voids & vugs!
- This comprises a third network, so…
- Vuggy NFCR’s have three contiguous flow systems, and $k_{fractures}$ is very $\sigma'$ sensitive!
Dolomitization involves the general reaction at depth:

$$\text{CaCO}_3 \rightarrow \text{CaMg(CO}_3\text{)}^2$$

with a large diminution of volume. This results in new voids, generally macrovoids, being created. These are called "vugs", and the system is called "vugular porosity", distinct from the matrix and from the natural fractures.

_Vugs - Grosmont Formation, Alberta_  

Courtesy: Alberta Geological Survey via Dr. Jose Alvarez
...and, Buried Karstic Features!

- Large solution caverns formed when the limestone was near the surface:
  - Joints are dissolved to form wide channels
  - Caverns are dissolved
- Then, these get buried, and...
  - Infilling with sand, clay
  - Collapse of structures
  - Opening of closed fractures
- Furthermore, these features have no lateral continuity, very difficult to detect remotely
Karst Examples

Fractures sub-parallel and orthogonal to cutting face

Fault zone with ~1m throw

Original fault-fracture systems show control of fluid movement (leaching & cementation)

Both sets of fractures with dissolution, but greatly enhanced at intersections

Jebel Hafit
Eocene Rus / Dammam Fms., Fault-fracture related karsts
Karstification - Grosmont Formation

Courtesy: Alberta Geological Survey via Dr. Jose Alvarez
NFCR’s

- Host 50-60% of the world’s conventional oil endowment
- Over 45% of these NFCR’s are found in the Middle East
- Now responsible for 40% of the world’s total daily heavy oil production
- Super giant fields produce massively (e.g. Ghawar field in Saudi Arabia (5.0 MMBOD))
- However, Ghawar and other NFCR’s are experiencing large problems now – $\text{H}_2\text{O}$
Problems with Seismics and NFCR’s
NFCR – Heavy Oil

Viscous oil oozing from a carbonate reservoir in South Kuwait

Natural fractures
NFCR’s

- Known for poor interrelationships between porosity, permeability and other properties ($CO_3$ rocks must be classified to improve this)
- Extremely low matrix $k$, yet fluids flow easily through fractures, karstic cavities and vugs.
- Very high initial production and rapid decline are typical of NFCR’s with low matrix $k$
- Classical evaluation techniques usually fail in carbonate reservoirs
- Challenges: reservoir characterization, GEM assembly, modelling and simulation; predictions
Sarvak Fmn., Kuh-e Mond NFCR
This step-rate test shows a strong effect of $\Delta p$ on $k$!

Water Disposal Well Assessment, Umm Er Radhuma Formation, Abu Dhabi

$p_{\text{inj}} < p_{\text{frac}}$

$p_{\text{inj}} - p_o$
What is Happening?

- Pressure increases in fractures tend to reduce the effective stress – $\sigma'$ - across fractures.
- This tends to increase the aperture of the fractures slightly…
- But the flow capacity of fractures is VERY SENSITIVE to the aperture.
Fracture Compression and Flow

\[ \Delta \sigma'_n \]
\[ \text{asperities} \]
\[ \text{effective aperture} \]
\[ p \rightarrow \Delta p \rightarrow p + \Delta p \]

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

\[ \Delta V \]

\[ \Delta T, \Delta \sigma', \text{strain and flow in fractured media are non-linear & stress-dependent} \]
The strong stress-sensitivity behavior of the permeability of NFCR’s means predictions of reservoir behavior are difficult.
Injection into a NFCR

Aperture dilation, k increase improve fluid flux

Extensional strain may open overlying vertical joints, impairing seal

water displacement, pressured zone
Δσ' - Closure & Hysteresis

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

Continued closure with cycles

Hysteresis

Normal Stress - MPa

Mechanical aperture - micrometers

Bandis - 1990
Are Joints Rough or Smooth?

Smooth joint

Rough joint

Source: N. Barton and A. Makurat
Here, we have a fracture-dominated flow system; the rock is being heated by a closed, high-T well. Thermal expansion increases $\sigma'_r$, and at the same time decreases $\sigma'_\theta$. This causes large increases in permeability in the carbonate as the fractures in certain directions open. **Coupled geomechanics!**
Geomechanics Issues in NFCR’s

- Blocky, dual porosity system (+vugs, karst…)
- Transmissivity of the fractures is highly stress and pressure sensitive
- Predictions of productivity?
- Well models do not work well in NFCR’s
- Stress changes can impair reservoir seal
- Add in T effects in heavy oil exploitation?
- A big challenge for geomechanics
- We must clarify the physics before we try to do a lot of engineering…
Different Joint Sets

5-D Fractured Carbonates

Source: N. Barton and A. Makurat
Are Fractures Open or Closed?

Source: N. Barton and A. Makurat
Fabric Issues

- The fracture pattern will dictate the well layout
- Is the cap rock a genuine seal for light phases (inert gas, steam, HC’s)?
- What is the spatial variability of the fracture network *in situ*?
- Will a high $\Delta p$ process ($\Delta \sigma'$) lead to fracture dilation and opening? Closing? Where?
- Will a high $T$ process lead to fracture dilation and opening? Closing? Where?
- Are these questions answerable?
Kuh-e Mond Structure

Qatar-Kazerun lineation

Fractures from image logs

Fractures from cores

5-D Fractured Carbonates
Permeability, Fabric and Scale

- Triple-permeability systems, generally:
  - Matrix – 1-50 m³ scale, $k \sim 5$-500 mD
  - Vugs – 0.5 – 100 cm³, isolated
  - Fractures – 0.5 – 5 m spacing, high $k$, low V
- Heterogeneity within and among matrix blocks can be intense
- Vugs are within blocks, some may not be directly connected to the fractures
- Also, karstified zones may exist
- Fracture fabric is important, and $\Delta \sigma'$!
The biggest geomechanics factor in NFCR’s is the stress-sensitivity of fracture flow.

This is a definitely non-trivial issue and affects all predictions (i.e. it affects risk and return).

Our models of fracture-dominated flow from wells in dual-porosity systems do not generally incorporate \( k = f(\sigma') \) (also, \( \Delta T \) effects!).

We have to use flow models empirically calibrated on similar materials, carefully…