Drilling Depleted Reservoirs

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Depleted Reservoir Effects

- Depletion of a zone has two major effects:
  - The lateral total stress, $\sigma_h$, drops
  - The effective stresses, $\sigma'_h$, $\sigma'_v$, both rise

- This results in:
  - A reduction of $P_F$ in the depleted zone
  - Increase in confining stress (= stronger rock)

- Consequences:
  - Slower drilling because rock is tougher
  - LC and blowout risks go up substantially
  - More casing strings, LCM squeezes, …

- More common recently (deeper targets)
Reservoir Depletion Effects

- $\Delta p$ leads to an increase in $\sigma'_v$, $\sigma'_h$ and a decrease in $\sigma_h$ ($S_h$). This is the Poisson effect, related to $\nu/(1-\nu)$ ($\nu =$ symbol for Poisson’s Ratio)

Increased $\sigma'$ means rock is stronger and tougher to drill. Are different bits required?

The $\sigma_h$ “lost” in the reservoir must be redistributed above and below the reservoir.
What Happens in the Reservoir?

- A “typical” reservoir is thin and laterally extensive, so $\sigma_v$ remains ~constant.
- No horizontal strains can take place.
- Thus, the horizontal total stress changes are governed only by the Poisson’s ratio effect and the change in pore pressure.

Inclined, folded, faulted cases are more complex (simulation).
New Fracture Gradient Calculation

- Determine depleted pore pressure in ppg
- Determine pore pressure change in ppg
- New $P_F$ is fracture gradient is:
  $$P_F = P_{F,i} + \Delta p \cdot \frac{1-2\nu}{1-\nu}$$
  - Where $P_{F,i}$ is the initial fracture gradient
  - $\Delta p$ is the change in reservoir pressure in ppg
    (remember, this is a $-$ve number)
  - $\nu$ is Poisson’s ratio, a dimensionless value
- You can do these in any units (density, ppg, MPa, psi), as long as you are consistent
All Stresses After Depletion

- All the new stresses can be calculated
- New pore pressure is $p_f$, change, $\Delta p = p_o - p_f$
- Initial $\sigma'_v]_i = \sigma_v - p_o$, final is $\sigma'_v]_f = \sigma_v - p_f$
- Horizontal effective stress change = $\Delta \sigma'_h = \Delta \sigma'_v \cdot \nu/(1-\nu) = -\Delta p \cdot \nu/(1-\nu)$ ($\Delta p$ is $-$ve)
- New horizontal effective stress = $\sigma'_h]_f = \sigma'_h]_i - \Delta p \cdot \nu/(1-\nu)$ (where $\Delta p$ is $-$ve)
- $P_F = \sigma_h]_f/z$ (density units where water = 1)
- Careful about the signs (+ve, -ve) of terms
Depletion Effect on $\sigma_h$

Operational consequences:
- low $p_F$ in reservoir
- higher $p_F$ above reservoir
- better fracture containment
Depletion and $\sigma_h$ (or $P_F$)

- The reservoir shrinks because of the drop in pore pressure
- Lateral stress – $\sigma_h$ – “arches” around reservoir
- To balance the drop in $P_F$, $\sigma_h$ above and below the zone must increase (equilibrium)
- Effects on vertical stress are small:
  - Because reservoirs are usually laterally extensive and thin in comparison to the depth
- So…$P_F$ is expected to be low in depleted zones
- Most serious in HTHP wells, multiple zones
Depletion Equation

\[ \Delta \sigma_h = \Delta p \cdot \frac{1 - 2v}{1 - v} \]

- This is the linear elastic equation for \( \Delta P_F \) (\( \Delta \sigma_h \)) for a horizontal laterally extensive reservoir.
- It is a good first guess for many cases.
- But, in fractured carbonates, Chalk, some other materials, an empirical approach is best.
- As usual, theory is tempered by practice…
Pressure decline leads to an increase in the shear stress
This can lead to shearing, which causes fractures and fissures to open
This leads to increases in permeability, better reservoir drainage
Exceptionally, it can lead to casing problems, etc.
Other Depletion Effects

- In some rare cases, the reservoir enters a condition of shear failure (or collapse)
- This may have beneficial effects on the reservoir itself (e.g. Ekofisk in North Sea)
  - Shearing in a dense rock opens fractures
  - Permeability goes up
- Of course, there may also be issues of casing shear (Dusseault *et al.*, 2001)
- ...and, free gas development in the reservoir
- Seismic velocities change, stiffness too

Depletion Failure Path, M-C Plot

This example is for a normal fault case, assuming $\sigma_v \sim$ constant

- $\tau$ – shear stress

MC - plot

Before $\Delta p$, initial
in situ conditions

Shear

After $\Delta p$

$a$ & $b$ stand for after and before $\Delta p$

Remember, these are effective stresses, not total stresses
Depletion to Shearing Failure

- Depending on the initial stresses (must be close to normal fault shear failure)
  - Depletion can lead to a condition of normal faulting ($\sigma_v = \sigma_1$)
- However, it is most easy to achieve in the case of a bounding normal fault
- In this case, the depletion of the zone leads to a lateral unloading of the fault plane
- And… slip occurs
Normal Fault Reactivation

\[ \sigma_v = \sigma_1 \]
\[ \sigma_{h\text{min}} = \sigma_3 \]

Stresses

Slip criterion: \[ \tau_{\text{max}} = c' + \sigma'_n \tan \phi' \]

\[ \sigma'_n = \sigma_n - p \]

Production

Drop in lateral stress through production

Normal fault plane

Also, effects of reservoir geometry (dip, thickness), \( C_c \), etc…
Depletion and Collapse Yield

Plastic crushing in a high $\phi$ UCSS

M-C plot

Crushing failure is contractile (-$\Delta V$), so $\sigma_h'$ drops more!

$\tau$ – shear stress

before $\Delta p$, initial \textit{in situ} conditions

$\sigma'_h|_b \quad \sigma'_h|_a \quad \sigma'_v|_b \quad \sigma'_v|_a$

$a$ & $b$ stand for after and before $\Delta p$

The “cap” part of $Y$, incorporates crushing
Collapse Yield

Pressure decline leads to an increase in the effective stress

Leading to crushing, which is accompanied by contractile behavior

...which leads to changes in permeability, perhaps for the worse
Irreconcilable MW in Depletion

MW limits cannot be reconciled! Special measures are required.

It is impossible to find a MW that both controls the pore pressure in thin adjacent undepleted sands, and also avoids LC in the depleted zone.

This effect is greatest in deep HPHT reservoirs that are massively depleted (large oil reservoir drawdown).
A Typical GoM Case

- A was discovered and depleted to $0.2p_o$
- Now, we want to drill through to B & C
- Or, A & B depleted, and our target is C
- Small gas sands are not depleted and present a blowout hazard
- Lowered $P_F$ in zones present a LC hazard
Gradient Plot, GoM Case

- Same as the previous plot, only now in mud density units.
- Colored lines are the original state of $p_o$, $\sigma$.
- $2.0 = 16.7$ ppg MW.
- Original target(s) A&B are depleted.
- The goal is to drill to Target C without:
  - Too many casings.
  - Lost circ, blowout.
- Challenging!
Example of Depletion Calculation

- \( p_o = 14 \) ppg, \( p_f = 4 \) ppg, \( \Delta p = -10 \) ppg
- \( P_{F|i} = \sigma_{hmin} = 16 \) ppg, assume \( \nu = 0.2 \)
- \( P_{F|f} = P_{F|i} + \Delta p \cdot (1 - 2\nu)/(1 - \nu) \)
- \( P_{F|f} = 16 \) ppg + [-10 \cdot (1 - 2 \times 0.2)/(1 - 0.2)] ppg
  - \( = 16 \) ppg \(- 7.5 \) ppg = 8.5 ppg
  - This is almost the gradient of \( \text{H}_2\text{O} \)!
  - Lost circulation will be unavoidable!
  - And, there will still be some thin 14 ppg gas sands above or below the zone to give you a blow-out!

- Let’s discuss choice of Poisson’s ratio
Choice of Poisson’s Ratio

- In very shaley sands, $\nu \sim 0.28 – 0.32$
- In clean sands, $\nu \sim 0.23 – 0.25$
- In fractured reservoirs, $\nu \sim 0.18 – 0.22$
- Extremely fractured, as low as 0.12 - 0.15
- You can use geophysical log estimates (~)
- Better, you can use calibrations based on real measurements, methods have been published
- It is best to calibrate to your own basin, so collect the data as it becomes available
Now, there is no MW possible to drill through the zones without exceeding $P_F$ or below $p_o$.

We need to find a new strategy for drilling.

Intact thin gas sands at original $p_o$

Two depleted reservoirs, low $P_F$

New target reservoir

Risks of blowouts, LC
The Casings & Liners Option

- Requires expensive casing strings or liners
- This approach usually results in two extra strings for each depleted zone
- Clearly, it is prohibitively expensive if there is more than one zone with active charged gas sands between
- Are there other options?
  - Yes, but there are some risks involved, or, there is additional time involved
- Let’s look at some options
Option One: Use Casings/Liners

- Drill to below A with 16 ppg MW, set casing
- Lower MW to 13 ppg, drill to B, set casing
- Raise MW to 16.7, drill to C, set casing
- Lower MW to 13.5 ppg, drill to D, set casing
- Raise MW to 16.7 ppg, drill to TD, set production casing/liner
- Now you have only a 5” hole and a 3.5” “casing”
Case with no Overlying Gas Sands

- This is a favorable condition:
  - Drill to bottom of depleted zone w. low MW
  - LCM squeeze in depleted zone to raise $P_F$
  - Raise MW to drill ahead, resqueeze if needed

- LCM squeezing is performed as much as necessary to raise MW to $p_o$ in gas sands

- However, remember the shales!
  - $p_o$ is still high in the shales
  - If MW < $p_o$(shale), massive sloughing possible
  - This option is similar to underbalanced drilling

- Thin undetected gas stringers remain a risk!
No Overlying Gas Sands

- Drill down to top of zone with as low MW as possible
- Add LCM to mud before you enter zone
- Build mud & LCM to keep up with losses
- Set casing below zone
- Increase MW to handle $p_o$ in gas sands
- Drill to Target
Depleting the Thin Gas Sands

- If the original wells are still available...
- Perforate into all the thin gas sands identified on logs or drilling records
- Deplete with maximum drawdown to reduce $P_F$ to the same as adjacent depleted zones
- Drill with low MW, set casing above target, increase MW, drill into target… Risks?
  - Some thin sands may be missed
  - Sufficient depletion is a lengthy process
  - Drill immediately after depletion and set casing as quickly as possible (low recharge time)
Living with Some Gas Influx

- If the gas sands are tight and thin…
- Gas influx rate may be manageable during drilling with the MW less than the pressure in the gas sands (underbalanced)
- Also, shales cannot be so weak that they slough into the hole with the low MW used!
- Mud de-gassers, gas collection from closed flow lines, etc. are safety measures
- This can be used only with great caution in the right circumstances
- Unlikely in sloughing shale regions
Is it Possible to Avoid the Zones?

- If the depleted zones are in a fault block, or are limited channel sands, avoidance...
- Using seismics, drill into zone to avoid the other zones
- Good stratigraphic/seismic data are vital
Can Old Wells be Re-Used?

- If the old wells are in good condition, they can be plugged carefully and used to drill

  - Squeeze with non-shrinking cement, perhaps patches too
  - Repeat squeeze perhaps?
  - Drill ahead (with bicenter bit?)
  - Install liner (expandable liner to save hole size?)
  - Complete the well

- Multilaterals are also possible…
LCM Squeezes in Depleted Zones

- Drill to just above the depleted zone with as low a MW as feasible
- Place high LCM mud at bit, and drill into zone OB; LC will occur, but will also tend to “pack off” the depleted zone
- Drill cautiously through zone, continuing to allow fracturing with the high LCM mud
- Once through zone, it may be advisable to close annulus and slowly squeeze extra LCM into the depleted zone
- Measure LOT in depleted zone for safety
How Does a LCM Squeeze Work?

Increased $\sigma_\theta$

Short, wide fractures created

This increases the stresses locally around the wellbore

Effect can be increased by repeated squeezes to make the tangential stresses higher in a larger zone around well

However, remember that does not increase stresses beyond the extent of the fractures. If a high $p_o$ is encountered lower, LC may take place.
Some Rig Capabilities Needed

- For drilling HPHT wells, and for drilling deep through depleted zones
- High & variable load capacity for riser and mud storage on offshore rigs
- High pump capability
- Large diameter kill line and choke line needed for quick response
- Early kick detection system
- Pressure sensors on BOP at mud-line level
- Gas handler on marine riser
- Pressure measurement devices on MWD
- LCM pill mixing facility for LCM squeezes
Depleted Zone Options Summary

- Use the old wells if possible
  - Deepen wells after zonal isolation
  - Can be used to deplete charged thin sands
- Can the new well trajectory avoid zones?
- Live with gas cut mud (if shales are strong)
- Drill with designed LCM material in mud
- Use LCM squeeze in depleted zones
- Place strategic casings and liners
  - Use bicentered bits, expandable casings to maintain reasonable hole diameter with depth
- Combine one or more of these options
Lessons Learned- Depleted Cases

- Depleted reservoirs present singular challenges for drilling
- Options include avoidance, use of LCM, multiple casings/liners, use of old wells...
- The risks involved are higher than in conventional reservoir development
  - Careful surveillance during drilling
  - Special drilling equipment...
- Bicenter bits and expandable liners represent a useful, albeit costly approach