Stress Changes during Production

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Production Engineering…

- Typical $\Delta V$ processes in production…
  - Pressure depletion leads to shrinkage
  - High p injection leads to expansion
  - Cooling leads to thermal shrinkage
  - Heating leads to thermal expansion
  - Solids production is a $-\Delta V$ process
  - Solids injection is a $+\Delta V$ process

- To simulate, predict and manage, we must understand and quantify these…

- Volume changes drive stress changes!
Example of $\sigma$ Redistribution

$\sigma_v$, $\perp$ section A-A'

$\sigma$ gain $\rightarrow$ $\sigma$ loss $\rightarrow$ $\sigma$ gain

$\int_A \sigma_\perp$ must be always constant

$\sigma_h$, $\perp$ B-B'

*-$\Delta p$ causes -$\Delta V$
**Δp-Induced Stress Changes**

- $\Delta V = -C_c \cdot \Delta \sigma'$ (linear approximation)
- Can we assume that $\Delta p = \Delta \sigma'$?
  - This is the widely used Terzaghi assumption
  - It is not valid in production geomechanics (see more detail in well test geomechanics section)
- What happens in a reservoir?
  - $\Delta p$ leads to some $\Delta V$, therefore some $\Delta \sigma'$
  - But, $\Delta V$ leads to redistribution of $\sigma_v$
  - Thus, $\sigma_v$ is not constant, hence $\Delta p \neq \Delta \sigma'$
- **Coupled modeling** is required to simulate $\Delta \sigma'$
Non-Linear Stress Changes

- From elasticity…
  \[ \Delta \sigma_h = \frac{1 - 2\nu}{1 - \nu} \cdot \Delta p \]
  - \( \nu \) = Poisson’s ratio
  - However, reservoirs behave differently
    - Geological history
    - Stress conditions
    - Porosity, rock type
    - …
  - Good data now exist

\( \sigma_{h\text{min}} \) in the reservoir

Pressure - p

(measure, theory)
Reservoir Stresses - Depletion

- Depletion changes the stresses
- This means that the following things happen:
  - The fracture gradient changes
  - The stiffness of the rock can change
  - The “drillability” of the rock may change (i.e. the strength can increase substantially)
- Also, in drilling into and through a depleted reservoir…
  - Blowout and LC risks increase
  - Extra casing strings often used

These effects can be remarkably costly if they are unanticipated!
Issues in Reservoir Stress Path

- What do we mean by the “stress path”
- How do we measure the stress path?
  - Hydraulic fracture tests, including MiniFrac™…
  - LOT, XLOT tests
  - Step-rate injection tests
- Can we predict the stress path in advance?
  - Theoretical approaches with mathematical models
  - Empirical methods, measurements, then models
  - Comparing to existing data bases (analogues)
Stress Definitions

We need 3 ppl stresses, 3 directions, & one pore pressure: seven parameters

We usually assume $\sigma_v$ is a principal stress

$\sigma_{HMAX} > \sigma_{hmin}$

$\sigma_{HMAX} > \sigma_{hmin}$

$\sigma_1 > \sigma_2 > \sigma_3$

$\sigma_a = \sigma_1$

$\sigma_r = \sigma_3$

$\tau_{max}$ planes

$\sigma_a$

$\sigma_r$

In Situ Stresses

Borehole Stresses

Principal Stresses

Triaxial Test Stresses
**Depletion Stress Path…**

- Depletion has two major effects…
  - Total lateral stresses drop ($\sigma_{\text{hmin}} \downarrow$ & $\sigma_{\text{HMAX}} \downarrow$)
  - Effective stresses rise ($\sigma'_v \uparrow$, $\sigma'_{\text{hmin}} \uparrow$, $\sigma'_{\text{HMAX}} \uparrow$)

- This results in the following…
  - $P_F$ drops in the depleted zone
  - Rock is stronger (confining stress increases)
  - Rock compacts (sometimes, a lot e.g.: Chalk)

- Consequences…
  - Slower drilling, incorrect bit choice in zone, well control risks (blowout, LC), more casing strings, LCM squeezes…
Pressure depletion leads to an increase in $\sigma'_v$, $\sigma'_h$ and a decrease in $\sigma_h$...

This is the “Poisson effect”, related to $\nu/(1-\nu)$

Increased $\sigma'$ means the reservoir rock is stronger and tougher to drill

The $\sigma_h$ “lost” must be redistributed above and below the reservoir

Blowout and LC!!
Stress Path: Using fracture tests, measure $\sigma_h$ at various $P_{res}$. 

**Equation:**

$$y = 10.9 + 0.90 \cdot x$$

**$R^2$:** 0.95
Hydraulic Fracture Test...

- Start pumping at a low rate
- Break-down pressure ($p_{BD}$)
- Fracture propagation pressure ($p_p$)
- Instantaneous shut-in pressure ($p_{ISIP}$)
- Fracture closure pressure ($p_{CL}$)

$\Delta p$ from flow effects

$\Delta p$ from flow into the formation

Initial mud pressure in the borehole ($>p_o$)

Stop pumping & shut-in pressure

$p$ decay by flow into the formation

Time (constant pumping)
Step Rate Test for $P_F$

At each stage, inject, select $p$ value consistently
Plot the data
Determine intersection
Step-Rate Tests Raw Data…

SFI Well 8R-26A: Step Rate Test (SRT)
Sep 27, 2008 (night shift)
Interpretation of Step-Rate Test...

BHP = 1,335.7 ft = 407.10 m
SFI Well 8R-26A: Step Rate Test (SRT)
Sep 28, 2008 (night shift)

FEP (1) = 4,260 kPa (617 psi)
FER (1) = 0.51 m³/min (3.3 bpm)
Grad (1) = 10.4 kPa/m (0.48 psi/ft)

FEP (2) = 5,862 kPa (850 psi)
FER (2) = 1.87 m³/min (11.7 bpm)
Grad (2) = 14.4 kPa/m (0.63 psi/ft)

Closure ~ 5,400 kPa (785 psi)

Matrix/HP flow
Fracture flow

Pmin ~ 2,546 kPa (369 psi)
Simultaneous Minifrac™ and SRT tests on wells in the North Sea show clearly that $P_F$ from SRT is not the same as $p_{CL}$ from a careful hydraulic fracture test. This shows the importance of quality control, consistency, and care.
Minifrac™ or SRT??

Two North Sea Fields - 2003

Difference: Thermal Effects!

Minifrac™: close to the wellbore only.
SRT, samples much larger volume, injects @ different T!
Injection leads to $\Delta T = \Delta \sigma'$...!!

- Waterflooding changes $T$
- Drop in $T$ causes rock shrinkage ($\Delta V = \beta \cdot \Delta T$)
- This causes a loss of lateral stress in the reservoir zone
- Locally, a lower $P_F$...
- Thus, the stress path is complicated by $\Delta T$
Repeated Measurements with $\Delta T$

A larger temperature difference leads to a larger drop in $P_{CL}$.
With continued depletion, the reservoir fracture gradient dropped from 1.65 to 1.44.
Why Predict the Stress Path?

- Assessment of the on-set of delayed sand production in wells (time & risk analysis)
- Design of hydraulic fractures and fracture containment analysis
- Predicting permeability changes, especially in fractured (mainly carbonate) reservoirs
- Evaluation and prediction of subsidence
- Drilling plans for asset redevelopment
- Drilling through the reservoir to access deeper targets (LC and blowout control)
Example: Fractured Rock & Stress

- Representative laboratory tests are not possible for the $k = f(\sigma')$ relationship
- Well tests after stress changes to determine $k$

**Rock vs Rock mass**

- Intact rock
- Single discontinuity
- Two discontinuities
- Several, etc.
- Rockmass

Stress path data can then predict changes in $k$!
**Exampe: Boundary Conditions**

- In the laboratory, for BC’s we use either:
  - No-lateral-strain (oedometric condition)
  - Constant stress

\[
\frac{\Delta V}{\Delta \sigma'} \quad \Delta \sigma \\
\text{Constant stress on all boundaries, 3-D compaction}
\]

\[
\frac{\Delta L}{\Delta \sigma'} \\
\text{No-lateral-strain on side boundaries, 1-D compaction}
\]
Laboratory Results

- Laboratory results from high quality core are useful, but insufficient.
- They allow you to estimate the behavior of a small specimen of rock.
- You can estimate the permanent strain response of the rock matrix.
- But, you cannot extrapolate directly to the reservoir.
In the Field...

- Must incorporate the stress path of rock mass!
- So that effects of $\Delta T$, $\Delta p$ are properly distributed
- BC’s of the reservoir are neither constant stress or zero displacement!
- This means that **real field measurements** of stress path are needed for model calibration, and use.
Data From Many Reservoirs

The response of reservoirs is non-linear; each reservoir responds differently, but some generalizations are possible.

The relationship can be described by the equation:

\[ y = 0.5308x^2 - 0.2447x + 1.0983 \]

with a coefficient of determination of \( R^2 = 0.7665 \).

Data from 33 cases, 15 fields

Fracture gradient (MPa/100 m) vs. Pore pressure gradient (MPa/100 m)
Adriatic Basin

4-E Stress Changes During Production

Adriatic Gas Field

Virgin fracture pressure (MPa) vs. Virgin reservoir pressure (MPa)

The graph shows the relationship between the virgin fracture pressure and the virgin reservoir pressure. The equation of the line is given by:

\[ y = 1.5461x - 16.363 \]

with a goodness of fit of \( R^2 = 0.9958 \).
From Elastic Theory ($\varepsilon_h \sim 0$)

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

- **Assumptions**
  - Linear elastic behavior – constant $\nu$ - Poisson’s ratio
  - Flat-lying and laterally extensive reservoir
  - Uniform reservoir depletion, no arching effects

- **Poisson’s Ratio…**
  - If $\nu \sim 0.25$, $\Delta\sigma_h \approx 0.67 \cdot \Delta p$
  - If $\nu \sim 0.10$ (fractured rock), $\Delta\sigma_h \approx 0.90 \cdot \Delta p$
  - If $\nu \sim 0.40$ (highly ductile rock), $\Delta\sigma_h \approx 0.33 \cdot \Delta p$
Stress Path Behavior

Some of these early time effects are related to stress arching effects…
Reservoir Stress Path - I

- An operational parameter ($P_F$, drilling…)
- It cannot be measured in the lab because of:
  - Sample damage
  - Scale effects (especially with natural fractures)
  - Boundary conditions in lab are incorrect
- Therefore it is difficult to predict in advance
- However, it can be measured
  - Hydraulic fracture tests, several cycles is best
  - SRT – but be careful about thermal effects
  - Minifrac only measures $\sigma_{h\text{min}}$ near the wellbore
Reservoir Stress Path - II

- The stress path following by a reservoir is not linear, and strains can be largely permanent.
- The lateral total stress will decline, but it is difficult to predict exactly because of...
  - Non-linear stress-strain behavior
  - Presence of fractures in the reservoir
  - Other effects (e.g. massive cold water injection...)
- It is best to measure the stress path in real situations. However, some cautions...
  - Not on massive cold or hot fluid injection wells
  - Multicycle larger hydraulic fracture is best
Local drawdown stress change effects are not the same as those that occur upon reservoir-wide depletion.
General Drawdown: no more Arching

If large $\Delta p$ values maintained by aggressive production & injection, then uniform stresses will not develop over time.

4-E Stress Changes During Production

$\Delta z$

full subsidence develops

full recompaition triggered

when zones interact, arching is destroyed, full compaction occurs

stresses now “flow” uniformly without arching around zones
The nature of the stress changes will also be affected by stiffness differences, although these are not plotted here.
 Thermal Effects...

- Stress Path is affected by cooling or heating
- These lead to $-\Delta V$, $+\Delta V$ (eg $H_2O$ flood, steam)
- Massive $\Delta \sigma$ can therefore take place
- (Undrained $\Delta p$ in low permeability shales)?
- The approach to analysis is:
  - Calculate the volume changes in a coupled model
  - Apply to determine the stress changes
- For thermal effects, this requires good $\kappa$ data
- Also, $\beta_T$ data (thermal compressibility)
Some $\Delta T$ Consequences…

- Cool water injection to sustain pressure can lead to breaching of cap rock…
  - Shale cools, $-\Delta V, \sigma_h \downarrow$ until $< p$, fracturing…
  - Injection water is lost to adjacent zones

- Steam or hot water injection
  - Reservoir expands faster than shale
  - Shear of well casings at the interface

- However, shear dilation (high $p, T$) can be beneficial, giving higher $k_w$
  - An aid to heavy oil extraction processes
Shale Fracture by Cooling

Fracture breakthrough

thief zone, high k

thin shale, k ~ 0

fracture plane

sandstone, high k

low k shale

T distribution near well

T \text{ inj}

T \text{ o}

\sigma_v

p_{\text{o}}

p_{\text{inj}}

\sigma_{3,\text{final}}

\sigma_{3,\text{init}}

4-E Stress Changes During Production
Cooling-Induced Stress Changes

4-E Stress Changes During Production
Near-field stresses are altered by $\Delta T$, $\Delta p$

Temperature increase causes stresses to increase near fracture

- primary fracture
- secondary fracture
- heated zone
- fracture tip
- high pressure zone $p > \sigma_3$ (original)
ΔT and Shear Dilation

in weak rocks, such as many high porosity sandstones, dilation occurs during shearing.
Thermal Shearing

- Shearing: adjacent wells
- No shearing: overburden
- Region of high shear

\[\tau_{+ve} \quad +\Delta T \quad \sigma_{HMAX} > \sigma_v\]

\[\tau_{-ve} \quad \text{max shear} \quad \text{low shear stress because of symmetry of displacements around the well}\]
The “Inclusion Concept”

Stress trajectories

overburden deflection
Slip along interface

Reservoir

Zone of $-\Delta V$

Zones of low $\sigma_r$, high $\sigma_\theta$

Giving rise to shear of casing, microseismicity…
Production Issues and $\Delta \sigma$

- Very large changes in $T$, $p$, $V$...
- This leads to large stress changes
  - Shearing of bedding planes, faulting
  - Compaction, dilation, frac gradients, etc.
  - Changes in $k$ (fractured reservoirs)
- Coupled modeling is necessary
  - Compressibilities must be used $\Delta T$, $\Delta p$, $\Delta \sigma'$
  - Non-linearities are important
- Monitoring! ($\Delta p$, $\Delta \sigma$, microseismic, deformation...) and stress path clarification.