Production-induced stress change in and around a reservoir pierced by two salt domes: A geomechanical model and its applications

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Acknowledgements go to Dave Bateman, Kees Hindriks, Peter Fokker, Bernhard Hustedt, Paul van den Hoek, Arno van der Haak, Dirk Doornhof, Niels Dijksman, Ernest Ndong, and Peter Grant.
Format

1) Introduction and problem definition
2) Geomechanical model construction
3) Model results
4) Interpretation
5) Application
6) Conclusions
Depletion-induced reservoir compaction has several effects inside and around the depleting reservoir, including fault slip, total stress change, and subsidence, all affecting operations.

Basin geomechanical model has three sets of input parameters:

1) sedimentary and structural geology,
2) depletion from reservoir fluid-flow models
4) distribution of rock mechanical properties

\[
\Delta h = h_{ref} \times \left( \frac{\Delta S_{\text{vert}}}{\alpha} - \Delta P_{p} \right) \times C_{m,p}
\]

Biot-Willis coefficient
\[
\alpha = 1 - \frac{C_{r}}{C_{bc}}
\]

h is geobody thickness, \( S_{\text{vert}} \) is total vertical stress, \( P_{p} \) is pore fluid pressure, \( C_{m,p} \) is volumetric compressibility by depletion under uniaxial-strain conditions (axial compaction, no radial deformation)
How can we envisage the stress redistribution in the overburden?

**Model 1. Pancake**
The overburden weight is **not** (or hardly) transferred to the sides of the reservoir.

The total vertical stress in overburden and in the reservoir stay roughly the same.

**Model 2. Stress arch:**
The overburden weight is transferred to the sides of the reservoir.

The total vertical stress in overburden and in reservoir is thus reduced.
Hydrocarbon fields around salt domes: Often associated faulting

Figure 4. Faults at near Top Paleocene level on Mungo, Monan, and North and South Pierce, with inferred flow directions of Paleocene turbidites.
Problem definition

Geology of upper crust is not a pancake (= open-door statement)

Near salt domes, combined effect of structural and sedimentary geology plus a lateral variation in depletion and rock properties.

Sand production, wellbore stability, fracture gradient analysis, and hydraulic fracture modeling require correct input 3D stress states.

These will vary with depletion and position wrt salt dome.

Finite-element based geomechanical models can be useful, provided calibrated against proper field and experimental data.

We built such a geomechanical model, to study salt-sediment interaction during the depletion-induced reservoir compaction.
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Pierce-physics model: Salt dome with idealized shape

"Mickey Mouse" models to increase insight in geomechanics
Von Mises shear stress, after switching on gravity (year 1840)

\[ \sigma_{VM} = \sqrt{0.5\left[(S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2\right]} \]
Von Mises shear stress, after 5 years of creep (year 1845)

\[ \sigma_{VM} = \sqrt{0.5\left[(S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2\right]} \]
Von Mises shear stress, after 15 years of creep (year 1855)

\[ \sigma_{VM} = \sqrt{0.5 \left[ (S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2 \right]} \]
Von Mises shear stress, after 45 years of creep (year 1895)

\[
\sigma_{VM} = \sqrt{0.5 \left[ (S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2 \right]}
\]
Von Mises shear stress, after 159 years of creep (year 1999)

\[ \sigma_{VM} = \sqrt{0.5 \left( (S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2 \right)} \]
Von Mises shear stress, after 159 years of creep (year 1999) and 12 MPa depletion in 7 years (year 2006)

Salt dome takes up load from overburden, creating shear stresses. Salt dome is thus relatively stiff compared to surrounding sediments, over time scale of depletion (years)

\[
\sigma_{VM} = \sqrt{0.5 \left[ (S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2 \right]}
\]
First we created a meshed, bounded continuous surface for formations in GoCad. We built the salt, Forties, chalk and mudstone formations.
P21b: Von Mises stress in GEOMEC

\[ \sigma_{VM} = \sqrt{0.5\left((S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2\right)} \]

Initialization in 1840

Creep to 1855

Creep to 1895

Creep to 1996
Calibration to the initial stress state: Radial symmetry

Determine total vertical stress from integrated density logs

Determine ratio of pre-production isotropic total horizontal stress to the pre-production total vertical stress ($K_0$)

Tweak $K_0$ till good match is obtained between GEOMECC-computed and field-data-interpreted minimum total principal stress

![Graphs showing stress vs. depth and principal stress comparison](image)
Pierce GEOMEC model: salt-dome-induced stress orientation
Before start of production, after 160 years of creep

Result compare well with stress states interpreted from diapirism
Confidence that salt-sediment interaction is included in our model
Depletion (MPa), from before production to 3 points in time

Depletion in the Forties
Up to 14 MPa (about 2000 psi)

Note compartments separated by faults

Dec. 04  Dec. 08  Dec. 09
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<td>6) Conclusions</td>
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Change in total vertical stress per unit depletion, measured from start of production till December 2009.

\[ \gamma_v = \frac{\Delta S_v}{\Delta P_p} \]
Change in minimum total principal stress per unit depletion, measured from start of production till Dec. 2009

\[ \gamma_3 = \frac{\Delta S_3}{\Delta P_p} \]
Change in total vertical stress per unit depletion, measured from start of production till December 2009: **North Pierce only**

\[ \gamma_v = \frac{\Delta S_v}{\Delta P_p} \]

GEOMECE data were extracted from all cells around the salt dome, in the area shown (no South Pierce, no model edge)
Models for stress path coefficients $\gamma_v$ and $\gamma_3$ as a function of Forties formation dip: FE-cells in depth intervals of 100 meters
Models for stress path coefficients $\gamma_v$ and $\gamma_3$ as a function of elevation of Forties above the Forties that is nearly flat-lying.

$\gamma_3 = \frac{\Delta S_3}{\Delta P_p}$

$\gamma_v = \frac{\Delta S_v}{\Delta P_p}$

Graph showing the relationship between gamma and height above base plane (m):
- $y = -0.0001x + 0.7$
- $y = -1.769E-07x^2 + 5.225E-04x + 1.551E-02$
Models for stress path coefficients $\gamma_v$ and $\gamma_3$ as a function of Forties formation dip, averaged in bins of Forties formation dip.

\[ \gamma \]

\[ \gamma_3 = \frac{\Delta S_3}{\Delta P_p} \]

\[ \gamma_v = \frac{\Delta S_v}{\Delta P_p} \]
Format

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Lateral variation in reduction in $S_v$ (stress arching)

In vertical direction, salt bodies are relatively stiff compared to the surrounding mudstones, even though salt flows with time. Salt therefore takes on more overburden load as Forties compact (pillar effect). However, Forties close to salt are protected by a “stress shadow”, with $S_v$-reduction being less than in open basin.
Conceptual model for high total horizontal stress near salt

Two hypotheses:

1) Salt will deform and its boundary may move sideways away from its core, “towards” horizontally and vertically compacting Forties

2) High structural dip of 45 deg., + high elevation of 1000 m above base plane (effect of arching)
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Quantification of the effect of stress path on open-hole stress state as function of formation dip and perforation orientation

Input data effect of stress path coefficient on wellbore stability

<table>
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<tr>
<th>Case</th>
<th>Depth of burial (ft, TVDss)</th>
<th>Pre-production total vertical stress (psi)</th>
<th>Pre-production minimum total hor. stress (psi)</th>
<th>Pre-production maximum total hor. stress (psi)</th>
<th>Pre-production pore fluid pressure (MPa)</th>
<th>Dip reservoir (deg., from hor.)</th>
<th>Vertical stress path coeff.</th>
<th>Minimum total horizontal stress path coeff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9954</td>
<td>9394</td>
<td>7416</td>
<td>7910</td>
<td>4950</td>
<td>0</td>
<td>0.04</td>
<td>0.70</td>
</tr>
<tr>
<td>2</td>
<td>8958</td>
<td>8454</td>
<td>6674</td>
<td>7119</td>
<td>4616</td>
<td>15</td>
<td>0.10</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>7963</td>
<td>7515</td>
<td>5933</td>
<td>6328</td>
<td>4283</td>
<td>25</td>
<td>0.15</td>
<td>0.67</td>
</tr>
<tr>
<td>4</td>
<td>6967</td>
<td>6575</td>
<td>5191</td>
<td>5537</td>
<td>3950</td>
<td>35</td>
<td>0.29</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>5972</td>
<td>5636</td>
<td>4450</td>
<td>4746</td>
<td>3617</td>
<td>45</td>
<td>0.33</td>
<td>0.58</td>
</tr>
</tbody>
</table>

TVS grad. 0.95 psi/ft
Sh grad. 0.75 psi/ft
Sh grad. 0.8 psi/ft
PP grad. To base 0.45 psi/ft
Overpressure 500 psi/ft
HC density 0.70 g/cc
Brine density 1.03 g/cc
Saturation (initial) 80 %
Fluid density 0.77 g/cc
Application in perforation stability and sand production analysis

Done using the theory of linear elastic deformation around a perfectly cylindrical straight borehole, comparing computed stress states to Mohr-Coulomb shear failure criterion.

Knowing that sand production is mainly caused by development of high shear stress at wellbore wall and at perforations, we depict the maximum shear stress ($\tau_{\text{max}}$) at two points along the borehole.
Application in perforation stability and sand production analysis

Done using the theory of linear elastic deformation around a perfectly cylindrical straight borehole, comparing computed stress states to Mohr-Coulomb shear failure criterion.

Knowing that sand production is mainly caused by development of high shear stress at wellbore wall and at perforations, we depict the maximum shear stress ($\tau_{\text{max}}$) at two points along the borehole.

Perforations from infill wells will "experience" this $\tau_{\text{max}}$ from day 1
Quantification of the effect of stress path on open-hole stress state as function of formation dip and perforation orientation

Drilling of a vertical well, after 2000 psi depletion, stresses acting at horizontally-oriented perforations

Depth (TVDss, m)

Max. shear stress (at perforations), psi

- Green line: Perforation orthogonal to salt dome. Pancake world
- Red line: Perforation orthogonal to salt dome. GEOMECCalc. stress state
- Green dashed line: Perforation tangential to salt dome. Pancake world
- Red dashed line: Perforation tangential to salt dome. GEOMECCalc. stress state

Vertical well

Orthogonal

Tangential

Salt dome
Quantification of the effect of stress path on open-hole stress state as function of formation dip and perforation orientation.

Drilling of a horizontal well tangential to salt dome, 2000 psi depletion, stresses at oriented perforations.

- Perforation horizontal, Pancake world
- Perforation horizontal, GEOMEC_calc. stress state
- Perforation vertical, Pancake world
- Perforation vertical, GEOMEC_calc. stress state

Horizontal well
Quantification of the effect of stress path on open-hole stress state as function of formation dip and perforation orientation

Drilling of a horizontal well tangential to salt dome, 2000 psi depletion, stresses at oriented perforations

- Perforation horizontal, Pancake world
- Perforation horizontal, GEOMEC_calc. stress state
- Perforation vertical, Pancake world
- Perforation vertical, GEOMEC_calc. stress state

Horizontal well
Conclusions

- **Vertical wells:** Regarding wellbore stress, including stress path coefficients from a finite-element (FE) geomechanical model brings negligible benefit compared to a pancake-layered Earth.

- **Horizontal wells:** Neglecting salt-dome-induced stress path can lead to tens of percent of error in shear stress at the wellbore.

  - In horizontal well parallel to salt, vertical perforation are still more stable (to sand production) than horizontal perforations.

  - Including salt-sediment interaction increases shear stress at vertical perforations by 60%, but it decreases shear stress at horizontal perforations by 20%, compared to pancake Earth.

- Prediction of sand production in horizontal infill wells close to salt will probably improve when using input stresses from FE-geomechanical models with real geology and salt-flow-effects.

  - This may benefit reservoir performance and ultimate recovery.
Production-induced stress change in and above a reservoir pierced by two salt domes: A geomechanical model and its applications

Shell Exploration & Production

We thank the management of Shell and partners of the Pierce development for permission to present this paper.

Thank you. Any questions?
### Appendix:

Data used to study the impact of reservoir tilt on shear stress, and thus on likelihood of sand production, for simplified-geology model

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<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction angle</td>
<td>25</td>
<td>(-)</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>2.1</td>
<td>psi</td>
</tr>
<tr>
<td>Cohesion or internal shear strength</td>
<td>9.0</td>
<td>psi</td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td>28.1</td>
<td>psi</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.22</td>
<td>(-)</td>
</tr>
<tr>
<td>Hydrocarbon density</td>
<td>0.70</td>
<td>g/cc</td>
</tr>
<tr>
<td>Brine density</td>
<td>1.03</td>
<td>g/cc</td>
</tr>
<tr>
<td>Saturation (initial)</td>
<td>80</td>
<td>% of pore volume</td>
</tr>
<tr>
<td>Pore fluid density</td>
<td>0.77</td>
<td>g/cc</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient in total vertical stress</td>
<td>2.15</td>
<td>kPa/m</td>
</tr>
<tr>
<td>Gradient in minimum total horizontal stress</td>
<td>1.70</td>
<td>kPa/m</td>
</tr>
<tr>
<td>Gradient in maximum total horizontal stress</td>
<td>1.81</td>
<td>kPa/m</td>
</tr>
<tr>
<td>Gradient in pore fluid pressure (normal regime)</td>
<td>1.02</td>
<td>kPa/m</td>
</tr>
<tr>
<td>Overpressure</td>
<td>3.4</td>
<td>MPa</td>
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<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>64.8</td>
<td>51.1</td>
<td>54.6</td>
<td>30.7</td>
<td>0</td>
<td>0.04</td>
<td>0.70</td>
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<tr>
<td>2</td>
<td>2700</td>
<td>58.3</td>
<td>46.0</td>
<td>49.1</td>
<td>28.4</td>
<td>15</td>
<td>0.10</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>2400</td>
<td>51.8</td>
<td>40.9</td>
<td>43.6</td>
<td>26.1</td>
<td>25</td>
<td>0.15</td>
<td>0.67</td>
</tr>
<tr>
<td>4</td>
<td>2100</td>
<td>45.3</td>
<td>35.8</td>
<td>38.2</td>
<td>23.8</td>
<td>35</td>
<td>0.29</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>1800</td>
<td>38.9</td>
<td>30.7</td>
<td>32.7</td>
<td>21.5</td>
<td>45</td>
<td>0.33</td>
<td>0.58</td>
</tr>
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Wrong model results can have two types of negative impact.

- In case of too optimistic forecasts of sand production (i.e. no sand or sand late in field life), wells may be lost by sanding-up in the early stages of the field life, with money wasted on well clean-ups and redrills.

- In case of too conservative sand-production forecasts, expensive sand-control equipment may be installed in wells that would not be producing sand under open-hole conditions, thus wasting money upfront by over-engineering a low-risk situation.

Basin-scale geomechanical analysis helps to gain insight in depletion-induced stress changes, also close to salt.

It leads to improved input in models predicting wellbore and perforation instability, and thus sand production risk.
Geomechanical effects of depletion-induced reservoir compaction

- Deformation, compaction or expansion, stress change and displacement **inside and around** the depleting reservoir

- Shear failure damaging wells and producing tremors
- Change in minimum total principal stress ("fracture gradient")
- Stress change affecting hydraulic fracture growth
- Subsidence
- Permeability change, often reduction with compaction

- Acoustic impedance changes and timeshifts in seismic
- Porosity reduction (compaction drive)
- Normal-fault slip connecting reservoir compartments