An integrated 4D seismic inversion workflow applied to the Catcher fields

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Harbour Energy (2)
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• Overview of the Catcher area fields
• Petro-elastic model calibration
• Deep Neural Network (DNN) inversion
• Bayesian inversion
• Uncertainty quantification

An Integrated Workflow for the Probabilistic Estimation of Pressure and Saturation Changes from 4D Seismic Data: Application to the Catcher Fields, Central North Sea
Gustavo Côrte, Sean Tian, Gary Marsden, Matthew Gibson, Colin MacBeth
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The Catcher area fields

- Clean sandstone injectites
- 35% porosity
- 3 Fields under development
  - Catcher, Varadero & Burgman
- Oil bearing Tay reservoir
  - Cromarty aquifer
  - Gas bearing attic sands
- Water injection (dedicated injection wells)
- Gas injection (intermittently through producer wells)
- Dedicated 4D seismic
  - ~3.5 years of production
  - High repeatability (NRMS ~11%)
The Catcher area fields

**Catcher**

Varadero

Burgman

Baseline Quadrature

**Catcher**

**Burgman**

**Varadero**

4D amplitude maps

Water injection (softening)

Gas injection (hardening)

No clear pressure signal

Baseline Quadrature

4D Seismic data

ΔSNA

Soft.

Hard.
Objective

4D seismic amplitudes

Reservoir property changes

- Pressure
- Water saturation
- Gas saturation
Petro-elastic model calibration

Hamed Amini and Colin MacBeth (2015)
“Calibration of rock stress-sensitivity using 4D seismic data.”
77th EAGE conference & exhibition, Madrid, Spain.

Hamed Amini (2018a)
“Calibration of minerals’ and dry rock elastic moduli in sand-shale mixtures.”
80th EAGE conference & exhibition, Copenhagen, Denmark.
Petro-elastic model (PEM)

Static model calibrated with:
- well log data

Dynamic model calibrated with:
- Lab data (core plugs)
- 4D Time-shift data

1) Mineral and Fluid elastic properties
2) Mixing laws

3) Porosity dependence (Dry frame moduli)
- Nur’s Critical Porosity
- Krief
- Cemented sand
- Soft sand
- Xu-White

4) Pressure sensitivity
- MacBeth (2004) equations
Static model calibration

Well log data:
- Density, Vp and Vs
- Multiple wells
- Global optimization algorithm
Dynamic model calibration

Core plug laboratory data

Shear Modulus

<table>
<thead>
<tr>
<th>Effective Pressure (psi)</th>
<th>$\kappa_{LSS}$</th>
<th>$\kappa_{HSS}$</th>
<th>$\mu_{LSS}$</th>
<th>$\mu_{HSS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Modulus</td>
<td>$\kappa_{LSS}$</td>
<td>$\kappa_{HSS}$</td>
<td>$\mu_{LSS}$</td>
<td>$\mu_{HSS}$</td>
</tr>
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<td>$\mu_{HSS}$</td>
</tr>
</tbody>
</table>

Time-Lapse Time-Shifts

Observed

Modelled
Deep Neural Network (DNN) inversion

DNN Architecture

- Variational Auto-Encoder
- Pixel by Pixel inversion
  - No lateral correlation constraints
- Regularization
  - Variational central layer
  - Dropout regularization
  - Train with noisy synthetic data
Synthetic training dataset

- Reservoir simulation results
  - 15 time-steps

- Synthetic 4D seismic maps

\[ \Delta P_{(MPa)} \quad \Delta Sw \quad \Delta Sg \]

\[ -5 \quad 0 \quad 5 \quad -0.7 \quad 0.7 \quad -0.15 \quad 0.15 \]

\[ \Delta Sg \quad -0.15 \quad 0.15 \]

\[ \Delta P_{(MPa)} \quad -5 \quad 5 \]

\[ \Delta Sw \quad -0.7 \quad 0.7 \]

\[ \Delta Sg \quad -0.15 \quad 0.15 \]

\[ \text{softening} \quad \Delta SNA \quad \text{hardening} \]

Sim2Seis
Synthetic training dataset

- Reservoir simulation results
  - 15 time-steps

- Pressure increase always related to water injection
- Statistical correlation between:

\[
\begin{align*}
\Delta P_{(MPa)} & \quad \Delta Sw \quad \Delta Sg \\
0 & \quad 0 & \quad 0.15 \\
5 & \quad 0.7 & \quad 0.15 \\
-5 & \quad 0.15 & \quad 0.7 \\
\end{align*}
\]

\[
\begin{align*}
\Delta P & = 5 \\
\Delta Sw & = 0.7 \\
\Delta Sg & = 0.15 \\
\end{align*}
\]

\[
\begin{align*}
\rho_{\Delta P,\Delta Sw} & = 0.26658 \\
\rho_{\Delta Sw,\Delta Sg} & = 0.010527 \\
\rho_{\Delta P,\Delta Sg} & = -0.011993 \\
\end{align*}
\]
DNN Inversion results

Training data property correlation
Water injection
Pressure increase

Pressure Results
Pressure increase in hardening signal regions

DNN Inversion Results
Varadero Field

Seismic Data

Simulation

Pressure increase in hardening signal regions
DNN Inversion results

Training data property correlation
Water injection
Pressure increase

Pressure Results
Pressure increase in hardening signal regions

Burgman Field

DNN Inversion Results

Seismic Data

Simulation

Pressure increase in hardening signal regions
Bayesian Stochastic Inversion

Bayesian Stochastic Inversion

**Prior Estimation**

-5 \(\Delta P\) (MPa) 5

\(-0.7 \leq \Delta Sw \leq 0.7\)

\(-0.15 \leq \Delta Sg \leq 0.15\)

**4D Seismic Data**

- Data correlations from seismic dataset
- 4D seismic uncertainty
  - \(\text{NRMS}\)

- Stochastic Markov-Chain Monte Carlo

**Prior Information**

- Reservoir simulation results
- Property correlations from training dataset
- Well pressures (BHP)

**Posterior**

- Prior Uncert.
- Likelihood
  - Data Uncert.
- Final Result
  - Result Uncert.
Bayesian Stochastic Inversion

- Pressure results: noise
- Residual hardening

Prior information:
- No prior information
- Zero change values everywhere
Bayesian Stochastic Inversion

- Pressure results: simulation
- Saturation results: slightly higher to compensate for the imposed pressure signal
- Residual hardening

- Prior information
  - Pressure: reservoir simulation
  - Saturation: Zero change values
Bayesian Stochastic Inversion

- Pressure results: simulation
- Saturation results: slightly higher than previous and also the DNN prior values
- Residual hardening gone

Prior information
- Pressure: reservoir simulation
- Saturation: DNN inversion
Uncertainty quantification
Low water saturations require pressure increases lower than +2 MPa to match seismic data.
High water saturations require pressure increases as high as +5 MPa to match seismic data.
Uncertainty quantification

- Probability of water saturation increase above a certain threshold
Conclusions

• **DNN inversion** provides a quick solution
  • Unbiased by prior information such as a reservoir simulation model
  • Incorporates global prior information: property correlations from fluid flow physics
  • Pressure estimations are reasonable, but inaccurate
  • Lack of uncertainty estimation

• **Bayesian inversion** adds to the information content
  • Reservoir simulation pressure prior
    • Likely more accurate than without, but biased by reservoir simulation results
  • DNN saturation prior
    • Better match to the 4D seismic data
  • Uncertainty quantification
    • Multiple realizations that match the 4D seismic data
    • High and low uncertainty bounds
    • P10 and P90 estimations
Acknowledgements

- Harbour Energy and Catcher JV partners
- Colin MacBeth
  Hamed Amini
  Jesper Dramsch

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