An example of constraining well test interpretation with the help of seismic

By
Hamidreza Hamdi
Patrick Corbett
Andrew Curtis (Edinburgh Uni.)
Colin MacBeth

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Outline

• Overview of Well Testing
  – Information obtained from well test
  – Importance of Model recognition

• An integration example
  – Stratigraphic discontinuity detection (4D seismic)
  – Numerical well-test interpretation
    • Deterministic approach
    • Inverse approach

• Conclusions
Information obtained from well testing

- Reservoir Description
  - Permeability (horizontal and vertical)
  - Heterogeneities (fractures, layering, change of properties)
  - Boundaries (distance to boundaries and shape)
  - Pressure (initial and average)

- The inverse problem

- Model recognition (S)
  - Well test models are different from the geomodels in the sense that they are dynamic models and also it’s an average model.
Well test transient pressure response plot

\[ \Delta P' = \frac{\partial P}{\partial \text{SupT}} \text{ for General multirate} \]

\[ \Delta P' = \frac{\partial P}{\partial (\text{LogT})} \text{ for Draw-down} \]

\[ \Delta P' = \frac{\partial P}{\partial [(\text{tp}+\Delta t)/\Delta t]} \text{ for Build-up} \]

The trend of pressure derivative curve is important:

1. Slope \( \rightarrow \) Flow regime indicator
2. Value at stabilization \( \rightarrow = f(\text{permeability, thickness, porosity, rate, viscosity and Bo}) \)
3. The separation of \( \Delta P \) and \( \frac{\partial P}{\partial \text{SupT}} \) \( \rightarrow \) indication of Skin( change of permeability in very near well bore area)
Importance of model recognition

1. Linear barrier (Fault, pinch-out, unconformity,...)
2. Composite reservoir (Linear /radial)
   Porosity, Permeability, compressibility, viscosity and thickness change across an interface

Note: Transition is, sometimes, quite long and make it even more difficult to interpret the test
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**Transient Well testing and seismic:**
*Exploration stage - seismic helps in WT interpretation*

<table>
<thead>
<tr>
<th></th>
<th>Static 3D seismic</th>
<th>Dynamic Well test</th>
<th>4D seismic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal faults</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Reverse faults</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Strike-slip faults</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Meandering (connectivity)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Some issues**
- Resolution + noise + throw
- Flow effect
- Flow effect + noise + P-effect

**Requirements**
- Surface seismic
- 1. Permanent seismic
- 2. VSP - permanent data sensors
- 3. Short interval surface seismic monitoring
4D seismic capability of detecting a no-flow boundary

Fault illumination by 4D seismic with time

4D seismic detectability

$\Delta P > 200 \text{ psi}$

$P_w$

Radius

Time

$t_1$, $t_2$, $t_3$
Time lapse monitoring of transient well test response

$L =$ distance to no-flow boundaries
$2f =$ illuminated part of the no-flow boundaries

(Distinguished length of boundary by 4D signal)

$f = n \times L$, $n = 0, 1, ..., 5$

\[ \Delta P_{active\_well}(r, t) = P_i - P(r, t) = \frac{q}{2\pi T} \int_{0}^{\infty} \left( 1 - e^{-u^2t_{ro}} \right) \frac{J_1(u)Y_0(uR) - Y_1(u)J_0(uR)}{u^2[J_1^2(u) + Y_1^2(u)]} du \]

\[ \Delta P_T(r, t) = \sum_{i=4}^{\infty} \Delta P(r_i, t) \]

\[ u = \frac{r^2}{4\eta t}, \quad \rho = \frac{r}{r_w}, \quad t_B = \frac{\eta t}{r_w^2} \]

We then try:

1. Single Flow boundary at distance “L”
2. Single no-flow boundary at distance “L2”
3. Two parallel no-flow boundaries (“2L”)

Active well
Image well
Required lapsed time from base seismic to monitor in order to illuminate a specified part of the boundaries.
Required lapsed time from base seismic to monitor in order to illuminate a specified part of the boundaries (sensitivity to permeability)

Parallel no-flow boundaries
sensitivity to permeability

Illuminated section index, FI
Illuminated length (ft) = FI*200

Single draw-down
q=1500 STBD
ϕ=0.18
h=100 ft
μ=1.5 cp
Bo=1.25
L=100 ft
ΔP=400 psia

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Practicality</th>
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</thead>
<tbody>
<tr>
<td>&lt;1-2 Days</td>
<td>Inter-Survey</td>
</tr>
<tr>
<td>2 Days to 1 Month</td>
<td>Not practical due to cost</td>
</tr>
<tr>
<td>1 to 3 Month</td>
<td>Permanent survey</td>
</tr>
<tr>
<td>1 to 3 Years</td>
<td>Surface seismic</td>
</tr>
</tbody>
</table>
Well testing and Seismic Example

- **Seismic can help well test interpretation**
  - Major Faults (3D Seismic)
  - Sub-seismic faults (3D & 4D)
  - Permeability baffles (4D)

- **Numerical well test interpretation**
  - Deterministic permeability profile + seismic
  - Inverse mobility and diffusivity map + seismic
    - Laplacian operator as a sectorization operator
Numerical Well Testing

Commingled braided Fluvial reservoir (Complex pressure response)

How to limit our well test interpretation based on the available seismic data?
Is the deviation is related to Faults, Boundaries or M contrast?

1. Channel behaviour? Too short?
2. Derivative trend between 1/4 and 1/5?
3. Structural Framework or property effect?
4. Validation of Interpretation
Idea: Can seismic help in Interpretation: Synthetic seismic

To detect:
1. No-flow boundary
2. Pressure effect on 4d seismic

We need:
A monitor as close to the end of test

RMS amplitude map of 4D response
Deterministic well test permeability profile

\[ m^* = \frac{\partial P}{\partial \ln t} \]

\[ K_i(t)h = q\mu B/m^* \]

Walking permeability

\[ \frac{1}{k_i} = \frac{1}{k_{in}(r_i)} - \frac{r_i}{2k_{in}^2(r_i)} \left[ \frac{dk_{in}(r)}{dr} \right]_{r_i} \]

Well test composite regions

Seismic "bin" size ~ 82 ft

Well test investigation radius: few ft to \( \infty \)

Seismic

\[ r_{inv} = 0.032 \sqrt{\frac{kt}{\varphi \mu c_i}} \]

\[ r_{inv} \approx 0.032 \sqrt{\frac{k t}{\varphi \mu c_i}} \]
A. Seismic Integration Into WT interpretation: Deterministic approach

\[
\frac{1}{k(r_i)} = \frac{1}{k_{in}(r_i)} - \frac{r_i}{2 k_{in}^2(r_i)} \left[ \frac{dk_{in}(r)}{dr} \right]_{r_i}
\]
A. Seismic Integration Into WT interpretation: Deterministic approach- Matching...

1. Poor quality of match at least before fault effect
2. Permeability (or M ratio) of each sector is within the range used in the reservoir modelling (<1000 md) and obtained based on the MYA
B. Seismic Integration Into WT interpretation:

Seismic Sector MAP

\[ \Delta \text{RSM-A} \]

Sector-Map & Seismic Structure

Gridding Single-Phase Sim.
B. Seismic Integration Into WT interpretation: (Seismic Sector MAP)-Matching...

1. Good quality of match
2. Permeability (or M ratio) of each sector is within the range used in the reservoir modelling (<1000 md)

Base K = 190 md

<table>
<thead>
<tr>
<th>Region</th>
<th>M</th>
<th>D</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>10</td>
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<tr>
<td>3</td>
<td>2</td>
<td>2</td>
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<tr>
<td>4</td>
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<td>5</td>
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<td>6</td>
<td>1.2</td>
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<tr>
<td>7</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
<td>1</td>
</tr>
</tbody>
</table>
B. Seismic Integration Into WT interpretation: sectorization by Laplacian

1. Laplacian is Local average operator: If Laplacian is positive then is locally less than the nearby average value.

2. Laplacian shows the front of higher changes!

3. It can be used as a reagon identifier to be used in sector composite map (NWT)
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• Conclusions
• Well test interpretation was constrained
• Larger faults mapped out using 3D & 4D seismic
• Permeability baffles were realized by 4D signal
• Numerical well testing was performed using the information from seismic data – reduce the uncertainty in model detection
• 4D & 3D seismic help sectorize the map used in numerical well testing software
• reasonable match obtained by integration of numerical well testing and seismic
Acknowledgements

- Schlumberger
- Weatherford
- Kappa
References

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