“Pre-Stack” Time-Shifts
New Paradigm for 4D Geomechanical History Matching

S.Izadian, C.MacBeth
Heriot-Watt University
\[
\frac{\Delta v}{v} = -R \varepsilon_{zz}
\]

- Vertical Rays
- Vertical Strain
- Isotropic

*Hatchell and Bourne (2005); Roste et al. (2006)*
Post-Stack 4D Geomechanics

Post-Stack Time-Shift ($\Delta t_{obs}^{post}$)

Geomechanical Simulation ($\varepsilon_{33}$)

Initial R-Factor

Time-Shift Modelling ($\Delta t^{mod}$)

Update R-factor

No

is $||\Delta t_{obs}^{post} - \Delta t^{mod}|| < \sigma$ ?

Yes

Calibrated R-Factor
Why Pre-Stack Domain?

*Herwanger et al. (2007)*
Pre-Stack R-Factor Model

\[
\frac{\Delta v}{v}(\theta) = \left[ -(R_1 - R_2)\varepsilon_{zz} - R_2 \varepsilon_{vol} \right] + \\
\left[ (R_1 - R_2)(\varepsilon_{zz} - \varepsilon_h) + (R_1 - R_2)\varepsilon_{vol} \right] \sin^2(\theta) \cos^2(\theta) + \\
\left[ (R_1 - R_2)(\varepsilon_{zz} - \varepsilon_h) \right] \sin^4(\theta)
\]

- Non-vertical Rays
- Lateral & Vertical Strain
- Anisotropic
- Two R-Factors

*Izadian and MacBeth (2022)*
Pre-Stack 4D Geomechanics

Pre-Stack Time-Shift ($\Delta t_{pre}^{obs}$)

Geomechanical Simulation ($\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}$)

Initial R-Factors

Pre-stack Time-Shift Modelling ($\Delta t^{mod}$)

Update R-factors

No

is

$\|\Delta t_{pre}^{obs} - \Delta t^{mod}\| < \sigma$?

Yes

Calibrated R-Factors
Application to North Sea Data

- Compacting reservoir.
- Pressure from flow simulation.
- Vertical strain from geomechanical simulation.

- Seismic and pressure may differ.
- R-factor measurement is semi-quantitative.
Pre-Stack Time-Shifts
Post-Stack Time-Shift vs Pre-Stack Time-Shift

- Massive drop in time-shift at far offsets (1.5 ms).
- Very non-linear behaviour.
- Post-stack time-shift is far from average.

- Massive increase in time-shift (2 ms) from near to far offsets.
- Post-stack time-shift is close to average.
- Post-stack time-shift is controlled by mid offsets.
Pre-Stack R-Factors

<table>
<thead>
<tr>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
<th>$R_1 : R_3$</th>
<th>$R_2 : R_3$</th>
<th>$\Delta \delta$</th>
<th>$\Delta \varepsilon$</th>
<th>Lithology</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>227</td>
<td>96</td>
<td>-116</td>
<td>-1.9</td>
<td>-0.8</td>
<td>0.1</td>
<td>0.1</td>
<td>North Sea Shale</td>
<td>Prioul et al. (2004)</td>
</tr>
<tr>
<td>207</td>
<td>38</td>
<td>-16</td>
<td>-12.9</td>
<td>-2.4</td>
<td>0.2</td>
<td>0.2</td>
<td>Colton Sandstone</td>
<td>Prioul et al. (2004)</td>
</tr>
<tr>
<td>626</td>
<td>-24</td>
<td>-21</td>
<td>-29.4</td>
<td>1.1</td>
<td>0.6</td>
<td>0.6</td>
<td>Berea Sandstone</td>
<td>Sarkar et al. (2003)</td>
</tr>
<tr>
<td>363</td>
<td>53</td>
<td>-8</td>
<td>-46.0</td>
<td>-6.8</td>
<td>0.3</td>
<td>0.3</td>
<td>Buff Sandstone</td>
<td>Winkler and Liu (1996)</td>
</tr>
<tr>
<td>465</td>
<td>144</td>
<td>55</td>
<td>8.5</td>
<td>2.6</td>
<td>0.3</td>
<td>0.3</td>
<td>Hanson Sandstone</td>
<td>Winkler and Liu (1996)</td>
</tr>
<tr>
<td>2536</td>
<td>545</td>
<td>154</td>
<td>16.5</td>
<td>3.5</td>
<td>2.0</td>
<td>2.0</td>
<td>Massilon Sandstone</td>
<td>Winkler and Liu (1996)</td>
</tr>
<tr>
<td>140</td>
<td>39</td>
<td>17</td>
<td>8.0</td>
<td>2.2</td>
<td>0.1</td>
<td>0.1</td>
<td>Portland Sandstone</td>
<td>Winkler and Liu (1996)</td>
</tr>
<tr>
<td>1237</td>
<td>348</td>
<td>19</td>
<td>66.0</td>
<td>18.6</td>
<td>0.9</td>
<td>0.9</td>
<td>Westerly Sandstone</td>
<td>Winkler and Liu (1996)</td>
</tr>
<tr>
<td>843</td>
<td>162</td>
<td>-156</td>
<td>-5.4</td>
<td>-1.0</td>
<td>0.7</td>
<td>0.7</td>
<td>Berea Sandstone (a)</td>
<td>Winkler and Liu (1996)</td>
</tr>
<tr>
<td>1686</td>
<td>402</td>
<td>121</td>
<td>13.9</td>
<td>3.3</td>
<td>1.3</td>
<td>1.3</td>
<td>Berea Sandstone (b)</td>
<td>Winkler and Liu (1996)</td>
</tr>
</tbody>
</table>

- Lab measurements can be orders of magnitude larger than field measurements.
- $R_2$ is a fraction of $R_1$.

*MacBeth and Bachkheti (2022)*
Anisotropic $\Delta v/v$
3 R-Factor Models

1) Post-Stack:

\[
\frac{\Delta v}{v} = -R\varepsilon_{zz}
\]

2) Pre-Stack, Isotropic:

\[
\frac{\Delta v}{v} = - (R_1 - R_2) \varepsilon_{zz} - R_2 \varepsilon_{vol}
\]

3) Pre-Stack, Anisotropic:

\[
\frac{\Delta v}{v} (\theta) = [- (R_1 - R_2) \varepsilon_{zz} - R_2 \varepsilon_{vol}] + \\
[(R_1 - R_2)(\varepsilon_{zz} - \varepsilon_h) + (R_1 - R_2)\varepsilon_{vol}] sin^2(\theta) cos^2(\theta) + \\
[(R_1 - R_2)(\varepsilon_{zz} - \varepsilon_h)] sin^4(\theta)
\]
Pre-Stack R-Factor Measurement

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Stack</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Pre-Stack Isotropic</td>
<td>8</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Pre-Stack Anisotropic</td>
<td>10.5</td>
<td>3.5</td>
<td>-</td>
</tr>
</tbody>
</table>

- $R_1 - R_2 \approx R$
- $R_2$ is a fraction of $R_1$. 

\[ R_1 - R_2 \approx R \]
Conclusions

- Time-lapse changes are indeed anisotropic.
- Lateral strain changes affect the 4D velocity changes.
- The proposed R-factor model captures the anisotropy in 4D changes.
Acknowledgements

We thank the sponsors of the Edinburgh Time-Lapse Project, Phase VIII (ADNOC, AkerBP, BHP, BP, CNOOC, ConocoPhilips, ENI, Equinor, ExxonMobil, Harbour Energy, Neptune Energy, Petoro, Petrobras, Sharp Reflections, Shell, TAQA, Tullow Oil, Woodside) for supporting this research.
Thank You