FAST: A New Approach to Risking
Fault Reactivation and Related Seal Breach

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FAST: Fault Analysis Seal Technology

- dead faults and live faults
- structural permeability
- FAST methodology
- Timor Sea examples
- discussion and conclusions
Dynamic Seal Breach: Timor Sea HRDZs

Dynamic Seal Breach: Timor Sea HRDZs

Hydrocarbon Seals

Seals
  - Caprock
  - Membrane
  - Fracture (Hydraulic)
  - Sealing Faults
  - Juxtaposition

Other
  - Hydrodynamic

After Watts (1987)
Hydrocarbon Seals

Seals
- Caprock
  - Membrane
  - Fracture
- Fault
  - Sealing Faults
  - Juxtaposition
  - Fracture/React
- Other
  - Hydrodynamic

Dead faults
Live faults

Jones et al. (2000)
Dead Faults or Live Faults?
Fault reactivation post-charge leads to breaching of the seal

Sibson (1992)
Effectiveness of Fracture Permeability

Matrix Permeability 1 mD
Ave. Permeability 1 mD

Fracture Aperture 0.25 mm
Matrix Permeability 1 mD
Ave. Permeability 13 510 mD
Failure Modes
Rock Failure

Griffith failure
\[ \tau^2 - 4T\sigma_n' - 4T^2 = 0 \]
tensile fracture

Shear fracture
\[ \tau = C + \mu_i \sigma_n' \]

Shear reactivation
\[ \tau = \mu_s \sigma_n' \]

Effective Normal Stress \( (\sigma_n') \)
### Structural Permeability

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Criterion</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile (hydraulic)</td>
<td>$P_p = \sigma_3 + T$</td>
<td>$(\sigma_1 - \sigma_3) &lt; 4T$</td>
</tr>
<tr>
<td>Tensile/shear</td>
<td>$P_p = \sigma_n + (4T^2 - \tau^2) / 4T$</td>
<td>$4T &lt; (\sigma_1 - \sigma_3) &lt; 6T$</td>
</tr>
<tr>
<td>Shear</td>
<td>$P_p = \sigma_n + (C_i - \tau) / \mu_i$</td>
<td>$(\sigma_1 - \sigma_3) &gt; 6T$</td>
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<td>Shear reactivation</td>
<td>$P_p = \sigma_n + (C_s - \tau) / \mu_s$</td>
<td>-</td>
</tr>
<tr>
<td>Stylolite</td>
<td>?</td>
<td>fine-grained matrix</td>
</tr>
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</table>

Sibson (1996)
Rock Failure

Shear Stress ($\tau$)

Effective Normal Stress ($\sigma_n'$)

Overpressure

Tensile Fracture

Shear Fracture

Shear Reactivation
Structural Permeability

Sibson (1996)
Structural Permeability: Mesoscale

Cosgrove (1995)
Structural Permeability

Potential recharge pathway

Potential along-fault flow pathway

Ferrill & Morris (2002)
Pore Pressure & Stress: Central North Sea

Gaarenstroom et al. (1993)
Hydraulic Seals and Hydrocarbon Retention Capacity, Central North Sea

\[ P_p > \sigma_3 + T \]
\[ R_c = \sigma_3 - P_p \]
\[ \sim \text{LOP-RFT} \]

Gaarenstroom et al. (1993)
In Situ Stress and Fracture Permeability

Barton et al. (1995)
In Situ Stress and Fracture Permeability

Barton et al. (1995)
Yucca Mountain

- Is Yucca Mountain, Nevada, a suitable site for a spent nuclear fuel and high-level radioactive waste repository?
Dilation Tendency

Dilation tendency is controlled by the magnitude of the normal stress

\[ T_d = \frac{\sigma_1 - \sigma_n}{\sigma_1 - \sigma_3} \]

Shear Stress

Normal Stress

\( \sigma_3 \) \hspace{1cm} \sigma_n \hspace{1cm} \sigma_2 \hspace{1cm} \sigma_1

Ferrill et al. (1999)
Slip Tendency

Slip tendency is defined as the ratio of shear stress to normal stress

$$T_s = \frac{\sigma_s}{\sigma_n}$$

Ferrill et al. (1999)
Ferill et al. recognise both modes of failure, but
- no consideration of rock properties
- separate analyses for each mode of failure
Fault Analysis Seal Technology (FAST)

- In Situ Stress Tensor
  - Mohr's Circle
  - Failure Envelop
  - Structural Permeability Development

- Fault Polygons
  - Centreline With Dip
  - Segment Fault

- FAST Map
\( \sigma_H^{\text{max}} = 82 \text{ MPa} \)
\( \sigma_H^{\text{min}} = 46 \text{ MPa} \)
\( \sigma_V = 64 \text{ MPa} \)
\( P_0 = 28 \text{ MPa} \)
\( \sigma_H^{\text{orient.}} = 156^\circ \text{N} \)

\( \sigma_{H} = 46 \text{ MPa} \)

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\( \phi = 28 \text{ MPa} \)

\( \sigma_{H_{\text{orient.}}} = 156^\circ \text{N} \)
Cataclasites in Pretty Hill Formation, Banyula-1, Otway Basin

\[ \tau = C + \mu \sigma_n' \]

\[ \tau = 5.4 + 0.78 \sigma_n' \]
\[ \sigma_{H_{\text{max}}} = 82 \text{ MPa} \]
\[ \sigma_{h_{\text{min}}} = 46 \text{ MPa} \]
\[ \sigma_v = 64 \text{ MPa} \]
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\[ \sigma_{H_{\text{orient.}}} = 156^\circ \text{N} \]
Acquired from seismic

Collapse fault polygons to centreline
FAST VI

ISS → MC → SP → FAST
FP → FE → CD → SF

Map showing various lines in different colors extending across the oceanic region with a color scale ranging from 0.0 to 1.0.
### Evidence for Seal Breach in the Timor Sea

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<th>HC Column Heights (m)</th>
<th>Residual Column Heights (m)</th>
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<th>ALF</th>
<th>Integrity</th>
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<td>24-38</td>
<td>-</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Intermediate</td>
</tr>
<tr>
<td>East Swan</td>
<td>0</td>
<td>90-215</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Low</td>
</tr>
<tr>
<td>Elang</td>
<td>73-76</td>
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<td>Y</td>
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Timor Sea Structural Permeability

Poles to planes southern hemisphere projection

SHmax = 055°N

ΔP (MPa)

45
28
11
Timor Sea Structural Permeability: Implications

- fault strike can vary as much as 60° and still maintain relatively low $\Delta P$ values (high risk) for dips > 50°
- $\Delta P$ can alter by as much as 15 MPa with only a change of 10° in dip magnitude
- confirms shear to be the most likely mode of failure
EAST SWAN PROSPECT

Risk of Fault Reactivation
Intra Jurassic Seismic Marker

East Swan No. 1 Well Completion Report (1977)
Elang

ELANG FIELD

Risk of Fault Reactivation near 'Break-up Unconformity'

Young et al. (1995)
Oliver

OLIVER FIELD

Risk of Fault Reactivation
Callovian Unconformity
Evans et al. (1995)
Skua

SKUA FIELD

Risk of Fault Reactivation
'Callovian et al. Unconformity'
Osborne (1990)
Observed vs. Predicted

The graph shows a comparison between observed and predicted risk levels across different locations. The x-axis represents different locations (Challis, East Swan, Elang, Oliver, Skua) while the y-axis quantifies the decreasing risk (increasing $\Delta P$ in MPa). The color coding indicates different levels of trap integrity:
- Red: Low
- Green: Intermediate
- Blue: High

The data suggests varying degrees of risk and trap integrity across these locations, with some locations showing higher predicted risk compared to observed data.
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Calibration Results

- Good correlation between observed fault trap integrity and FAST reactivation predictions
  - $\Delta P < 10 \text{ MPa} \Rightarrow$ Low integrity trap
  - $10 < \Delta P < 15 \text{ MPa} \Rightarrow$ Moderate integrity trap
  - $\Delta P > 15 \text{ MPa} \Rightarrow$ High integrity trap
Hydraulic Seals and Hydrocarbon Retention Capacity, Central North Sea

\[ P_p > \sigma_3 + T \]
\[ R_c = \sigma_3 - P_p \]
\[ \sim \text{LOP-RFT} \]

Gaarenstroom et al. (1993)
Skua 3D FAST

Mesozoic Faults

Tertiary Faults
Comparison of 2D and 3D FAST

- Lowest $\Delta P$ is similar between (approx. 12 MPa)
- 2D FAST remains a useful tool for first-pass, regional assessments of fault reactivation
Discussion

• reactivation causes breach
• timing of reactivation
• seal-breaching fractures vs. seismic faults
• present-day vs. palaeo-stresses
• variation in stress field
• variation in failure envelope
• sensitivity analysis
• pore pressure/stress coupling
Shear Stress

Effective Normal Stress ($\sigma_n - P_p$)

Initial state
overpressure

\[ \Delta \sigma \]

\[ v' \]

\[ \Delta \sigma \]

\[ h' \]

10

Shear Stress (MPa)

Effective Normal Stress \((\sigma_n - P_p)\)

\(-5\) \(5\) \(15\) \(25\) \(35\) \(45\) \(55\)

overpressure

\[ \Delta \sigma_h' \]

\[ \Delta \sigma_v' \]
Conclusions

- reactivation post-charge presents a risk of seal breach
- juxtaposition and fault rock analyses suffice for ‘dead’ but not ‘live’ faults
- tensile and/or shear failure impose dynamic limit to column height
- like other geomechanically-based techniques, for risking reactivation, FAST requires knowledge of fault orientation and the in situ stress field
- unlike other techniques, FAST incorporates the risk or tensile and/or shear failure into a single $\Delta P$ parameter
- unlike other techniques, FAST allows ‘real’ fault-rock failure envelopes to be incorporated
- risk may vary on faults with constant strike, hence it is a 3D problem: not just use fault maps
- FAST Map provides convenient method for analysing the problem in 3D for regional fault maps (from 2D seismic data)
- methodology incorporated into FAPS/Traptester for use on faults mapped using 3D seismic data
- calibration of FAST predictions is critical
- sensitivity analysis of FAST predictions is critical
Acknowledgements

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