Quantifying the heterogeneity of the stress field derived from local and global borehole data

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### WSM Quality Ranking

<table>
<thead>
<tr>
<th>Stress Indicator</th>
<th>A Quality</th>
<th>B Quality</th>
<th>C Quality</th>
<th>D Quality</th>
<th>E Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Borehole breakout</strong></td>
<td>( S_{H_{\text{max}}} ) believed to be within ± 15°</td>
<td>( S_{H_{\text{max}}} ) believed to be within ± 15-20°</td>
<td>( S_{H_{\text{max}}} ) believed to be within ± 20-25°</td>
<td>Questionable ( S_{H_{\text{max}}} ) orientation (± 25-40°)</td>
<td>no reliable information (&gt; ± 40°)</td>
</tr>
<tr>
<td>≥ 10 distinct breakout zones and combined length ≥ 100 m in a single well with s.d. ≤ 12°</td>
<td>≥ 6 distinct breakout zones and combined length &gt; 40 m in a single well with s.d. ≤ 20°</td>
<td>≥ 4 distinct breakouts and combined length ≥ 20 m with s.d. ≤ 25°</td>
<td>&lt; 4 distinct breakouts or &lt; 20 m combined length in a single well with s.d. ≤ 40°</td>
<td>Wells without reliable breakouts or s.d. &gt; 40°</td>
<td></td>
</tr>
<tr>
<td><strong>Drilling induced fracture</strong></td>
<td>≥ 10 distinct fracture zones in a single well with a combined length ≥ 100 m and s.d. ≤ 12°</td>
<td>with a combined length ≥ 40 m and s.d. ≤ 20°</td>
<td>with a combined length ≥ 20 m and s.d. ≤ 25°</td>
<td>zones in a single well or a combined length &lt; 20 m and s.d. ≤ 40°</td>
<td>Wells without fracture zones or s.d. &gt; 40°</td>
</tr>
</tbody>
</table>

**Two entangled concepts:**

**Measurement Quality vs. Stress Heterogeneity**

(from Heidbach et al., 2010)
Stress around wellbores

Good for near-vertical wells (DEVI<10°)
Non-linear and non-unique problem for larger deviations
Well deviations at Coso Geothermal Field

- 50% of well sections are deviated by more than 10° from vertical
Well deviations at Coso Geothermal Field

- 80% of deep* well sections are deviated by more than 10° from vertical

* below sea level
Coso Geothermal Field

- Young volcanic system
  - Most recent eruptions ~40 kyr ago
- Situated in the Eastern California Shear Zone
  - Transition from San Andreas Fault to Basin and Ranges systems
  - Accommodates ¼ of relative plate motion
- Geothermal exploration in 1970s – 1980s
  - 270 MW capacity online since 1990
  - > 170 wells drilled
Coso Geothermal Field
Well trajectories

58A-10^y

58-10^d
Approach to deviated wells

- Full inversion schemes do not provide details on non-uniqueness of best solution
  - Use a grid search instead
- Interpretation of stress indicators
  - Stress indicators in deviated wells do not coincide with stresses in geographic coordinates
    - Measure orientation relative to high side of well
- Assumptions
  - $S_v$ is a principal stress (same as with standard analysis of vertical wells)
  - Constant ratio of $S_{H_{max}}$, $S_{h_{min}}$ and $p_p$ to $S_v$
Grid search

- Perform grid search for best-fitting stress state
  - For each stress magnitude state given by $S_{H\text{max}} / S_v$, $S_{h\text{min}} / S_v$
  - For each orientation of $S_{H\text{max}}$
  - For each failure stress indicator

- Sum $\text{misfit}$ between observed and expected location
Best-fitting stress magnitude state – for any orientation of $S_{H\text{max}}$
Which $S_{H\text{max}}$ orientation for best-fitting stress state?
Best-fitting stress magnitude state – for any orientation of $S_{Hmax}$
Which $S_{H_{\text{max}}}$ orientation for best-fitting stress state?
How do best-fitting stress orientations compare?

- Difference of preferred orientations $|azi(S_{H_{max,58A-10}}) - azi(S_{H_{max,58-10}})|$

Orientation of $S_{H_{max}}$ agrees for both boreholes: N23°E
Local stress orientation
Local stress orientation

Standard deviations for both boreholes agree as well: SD=23°
Local stress map
Derived stress orientation vs. logged interval

58A-10^v

58-10^d

Deviation from mean [°]

Standard deviation [°]

Quality

Logged interval length [m]

WSM quality
- B
- C
- D
- E

Logged interval length [m]
Global World Stress Map borehole data

Heterogeneity of stress is a site characteristic
Stress heterogeneity vs. GSHAP

Rejected by reviewers

10% probability of exceedance in 50 years
Stress heterogeneity vs. GSHAP
Conclusions

- Deviated wells sample the stress field in different directions
  - Gather information about stress tensor in various orientations
  - Results can be non-unique
- Heterogeneity of stress is a site characteristic
  - Large standard deviation of about $23^\circ$ at Coso
  - Stress indicators spanning $\gtrsim 600$ m needed for a reliable stress characterization (orientation and standard deviation)
  - Correlation between stress heterogeneity and seismic activity suggested

(Almost) full story:

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