Dependency of the injection induced seismicity $b$-value on the stress state of existing fractures

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**Background**
- Magnitude frequency distribution is well characterized with a Gutenberg-Richter relationship $\log(N/V) = b \cdot M$. $b$-value is an important parameter to characterize seismic activity.
- The number of the studies on $b$-value from laboratory scale to plate boundary have led general understanding that $b$-value has negative correlation with differential stress.
- In the case of induced seismicity, $b$-value reduction was observed often at the high pore pressure condition and is used for seismic risk analysis.
- However, the cause of the $b$-value reductions for injection induced seismicity has remained unclear, since in the reservoir scale, significant increase of stress state is hardly expected.
- Therefore, the question to be addressed here is what is the physical explanation of $b$-value reduction for injection induced seismicity? (no stress dependency?)

**Field data & Methodology**

**Basel, Switzerland EGS project: (Hong et al., 2009)**
- Hydraulic stimulation to a depth of 5000 m in the injection well of granite session
- Microseismic monitoring at six downhole sensors.
- Around 2700 of events were located.

**Fault geometry:**
- Well-constrained fault mechanisms for around 100 of the larger events by Swiss seismological service (SED).
- Focal orientation from multiple (cluster) analysis for cluster members.

**Stress information:**
- Azimuth of $S_{max} = 234^\circ \pm 14^\circ$.
- $S_{max} = 0.001034 \times 155$, $S_{max} = 0.01990 - 17.78$.
- $\sigma_3 = 0.02492$, and $\phi = 0.00817$.

**Normalized shear stress**
- Normalized shear stress ($NSS = shear stress/differential stress$ at the depth/2 (radius of Mohr stress circle))
- NSS indicates the height of the given fault plane on Mohr stress circle.

**Magnitude frequency distribution**

Felzer, 2006

**Observations**

- $b$-value high: less large events
- $b$-value low: more large events

- Lower $b$-values of BG are always lower than those of LG for same NNS.
- For the BGs, $b$-values systematically decrease with NNS from 0.943 of BG (0.73) to 0.866 of BG (0.87).
- For the LGs, $b$-value decrease with NNS from 1.21 of LG (0.76) to LG (0.76) and (0.73) do not change significantly.

**Discussion & Conclusions**

- Our observations demonstrate clear $b$-value dependency on the NNS for injection induced seismicity.
- General understanding of $b$-value can be translated by considering well-oriented fault as $b$-value dependency on shear stress.
- As no significant driving force to increase differential stress is expected in reservoir scale, the events from high NNS fracture causes $b$-value reduction.
- We conclude that, on the reservoir scale condition, the reduction of $b$-value associated with the fluid injection is attributed to the occurrence of events along high shear stress fractures. This is consistent with general understanding of $b$-value reduction.

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b-value dependency on NNS for HG. Purple line corresponds to $b$-values estimated from events having stress state information.

- $b$-value dependency on NNS for LG. Green line corresponds to $b$-values estimated from all events.
- $b$-value from HG always shows lower value than averaging $b$-value.
- $b$-value from LG is more systematically decreasing and finally converge to averaging $b$-value.
- Both cases show $b$-value dependency on the NNS. $b$-values from HG are significantly lower than those from LG.

**Inclusion of high stress and effective normal stress**

- Effective normal stress and effective differential stress, expressed with PG (Pole gravity) and DD (difference differential) for high stress states. Stress states of the well oriented planes for each differential stress are shown in both plane fields. Effective normal stress is also showing the size of the fault coefficient of 0.4. The magnitude reduced seismicity, we assume as constant. Modified Coulomb failure plane for the constant condition. The events from NNS = 0.85 will be plotted in data shared area.