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

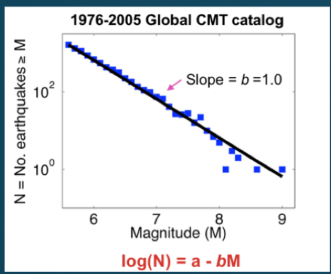
Yusuke Mukuhira[1,2], Michael Fehler[2], Takatoshi Ito[1], Hiroshi Asanuma[3], Markus Häring[4]

[1]Institute of Fluid Science, Tohoku University (Japan), [2]Earth Resources Laboratory MIT (USA), [3]FREA, AIST (Japan), [4]Geo Explorer Ltd., (Switzerland)

Background

- Magnitude frequency distribution is well characterized with Gutenberg-Richter relationship (log(*N*)=*a*-*b*M). *b*-value is the important parameter to characterize seismic activity
- The number of the studies on *b*-value from laboratory scale to plate boundary earthquake 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?)**

Magnitude frequency distribution



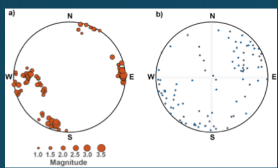
Felzer, 2006

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

Field data & Methodology

Basel , Switzerland EGS project: [Häring et al., 2008]

- Hydraulic stimulation to a depth of 5000 m in the injection well of granite session
- Microseismic monitoring at six downhole seismometers
- Around 2700 of events were located



a) Pole distribution of selected fault plane from FPSs estimated by SED. The sizes of the circles are scaled with the magnitude.

b) Pole distribution for the multiplet cluster consisted by more than five events.

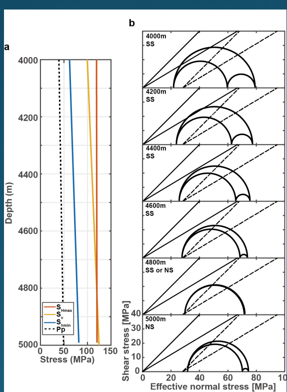
Fault geometry: [Deichmann and Giardini, 2009; Terakawa et al., 2012].

- Well-constrained fault mechanisms for around 100 of the larger events by Swiss seismological service (SED)
- Focal orientation from multiplet (cluster) analysis for cluster members

Stress information: [Valley and Evans, 2009, 2015].

- Azimuth of S_{Hmax} = N144°E ± 14°
- S_{Hmax} = 0.00104z + 115, S_{hmin} = 0.01990z – 17.78, Sv = 0.0249z, and Ph = 0.00981z

(z: depth from the surface (m), Ph: hydrostatic pressure [MPa]).

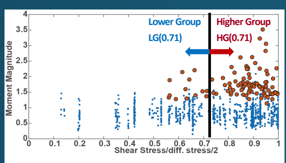


a) Stress magnitude profile as a function of depth.

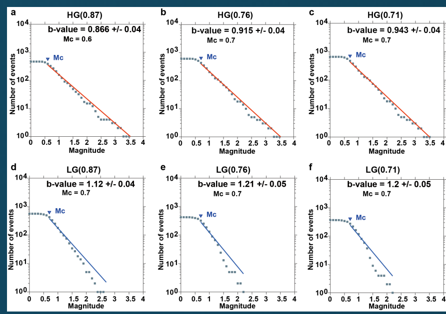
b) Mohr stress circles at selected depth with Coulomb failure criterion line for friction coefficient 0.6 and 1.0 (solid lines). Broken lines correlates pressurized conditions. Stress states (SS: strike slip, NS: normal fault slip) are shown in each panels.

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



Observations

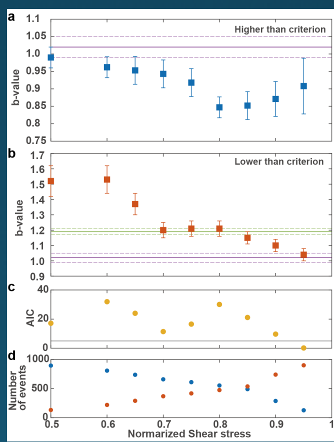


a) b) c) Magnitude frequency distribution for the events from shear stress higher than NSS.

d) e) f) Magnitude frequency distribution for the events from shear stress lower than NSS.

Three criterions correspond to the NSS for well oriented faults for friction coefficient 0.6, 0.85, and 1.0.

- The *b*-values of BG are always lower than those of LG for same NSS
- For the BGs, *b*-values systematically decrease with NSS from 0.943 of BG (0.71) to 0.866 of BG (0.87)
- For the LGs, *b*-value decrease with NSS from 1.21 of LG (0.87) to LG (0.76). *b*-values for LG (0.76) and LG (0.71) do not change significantly

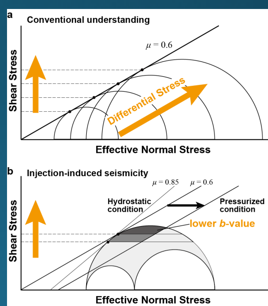


a) b-value dependency on NSS for HG. Purple line corresponds b-value estimated from events having stress state information
b) b-value dependency on NSS for LG. Green line corresponds b-value estimated from all events
c) Significance of the difference of *b*-values between HG and LG in the manner of Akaike's information criterion (AIC). The highly significant line of AIC=5 is shown with black line
d) Number of events used to estimate *b*-values for HG (blue) and LG (red)

- *b*-values from HG is overall decreasing systematically except last two plots. The *b*-values 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 NSS. *b*-values from HG are significantly lower than those from LG

Discussion & Conclusions

- Our observations demonstrate clear *b*-value dependency on the NSS for injection induced seismicity.
- General understanding of *b*-value can be translated by considering well-orientated 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 NSS 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.**



a) General understanding that *b*-value dependency on increasing differential stress expressed with bigger diameters of Mohr stress circle. Stress states of the well oriented planes for each differential stresses are shown with black. Coulomb failure line is showing the case of friction coefficient of 0.6.

b) Injection induced seismicity case considered in this study. Differential stress is assumed as constant. Shifted Coulomb failure line corresponds the pressurized condition. The events from NSS > 0.87 will be plotted in dark shaded area.

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