Seismogenic Index, Bounds of Magnitude Probability and Triggered versus Induced Earthquakes

S. A. Shapiro, O. S. Krüger, C. Dinske, C. Langenbruch.
Cumulative event number

The Gutenberg-Richter law:
\[ \log N_M = a - bM \]

The Gutenberg-Richter law for fluid injections:
\[ \log N_M (t) = \Sigma + \log Q_c (t) - bM \]
For Basel from tectonic data
(F. Wenzel 2011)

Seismogenic index, Σ

Basel: normalized cumulative seismicity and injected volume

- **injected volume**
- **$M > 0.5 (M_C)$**

![Graph showing time since first event (h) and shut-in time vs. seismicity and injected volume](image)
Basel: normalized cumulative seismicity and injected volume

- Dashed line: injected volume
- Red line: $M > 0.5 (M_C)$
- Orange line: $M > 1$
- Red line with dots: $M > 1.5$
- Pink line with dots: $M > 2$

Time since the first event (h)
Finite stimulated volume

Effect of the geometry

A power-law type of the probability of a rupture of the size $L$ produces the Gutenberg-Richter magnitude distribution:

$$W_F \propto L^{-2b - 1} \delta L$$

The following product takes effects of the geometry into account:

$$W_F(L)W_{\text{geometry}}(L)$$
The geometry of two bounds

W_{geometry}(L)

- $L_{\text{min}} = 10$
- $L_{\text{int}} = 50$
- $L_{\text{max}} = 400$
The bounds for magnitude distributions
The lower bound seems to be preferred!

- **ESG stage A data**
  - $b = 1.3325$, $a = 0.9022$
  - $\Delta \sigma = 920.602 \text{ kPa}$, $M_{\text{max}} = 0.29384$
  - $M_C = -1.51$

- **Soultz '93 data**
  - $b = 1.3512$, $a = 2.4742$
  - $\Delta \sigma = 659.418 \text{ Pa}$, $M_{\text{max}} = 1.4711$
  - $M_C = -0.71$
Induced and some triggered events!

- **Barnett Shale**
  - Lower bound
  - Gutenberg–Richter

- **Cotton valley B data**
  - Lower bound
  - Gutenberg–Richter

### GR and LB

**b** = -2.5412, **b** = 1.8803
**a** = -4.5488, **a** = -2.2365

\[ \Delta \sigma = 2.364 \text{ Pa} \]
\[ M_{\text{max}} = -1.6975 \]

\[ M_C = -2.7252 \]

**GR and LB**

**b** = 1.885, **b** = 1.1355
**a** = -0.86048, **a** = 1.1436

\[ \Delta \sigma = 17.864 \text{ kPa} \]
\[ M_{\text{max}} = -0.8475 \]

\[ M_C = -1.9748 \]
Impact on the Gutenberg-Richter parameters

![Graph showing impact on Gutenberg-Richter parameters with data points and lines representing different models.](image-url)
Reconstructed b-value vs apparent b-value

Carsten Dinske, 2015
The scale controlling maximum magnitudes

\[ M_L = \log L^2 + \frac{[\log \Delta \sigma - \log C]}{1.5} - 6.07 \]
Maximum magnitude vs minimum axis

\[ \text{MAX}\{M_{\text{max}}\} \approx 2 \log L_{\text{min}} - 1 \]
Conclusions

• Stimulated-volume geometry impacts statistics of activated rupture surfaces.

• The minimum principal axis of this volume and the stress drop control $M_{\text{max}}$.

• Both, $a$– and $b$– Gutenberg-Richter values are strongly affected.

• The geometry implies lower and upper bounds of magnitude probability.

• Induced seismicity tends to follow the lower bound.

• The bounds help to distinguish between induced and triggered events.

• Estimates of stress drops and $M_{\text{max}}$ are possible.