Modeling of the Pohang Earthquake Probability Using the Seismogenic Index

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The Gutenberg-Richter law of injection-induced seismicity

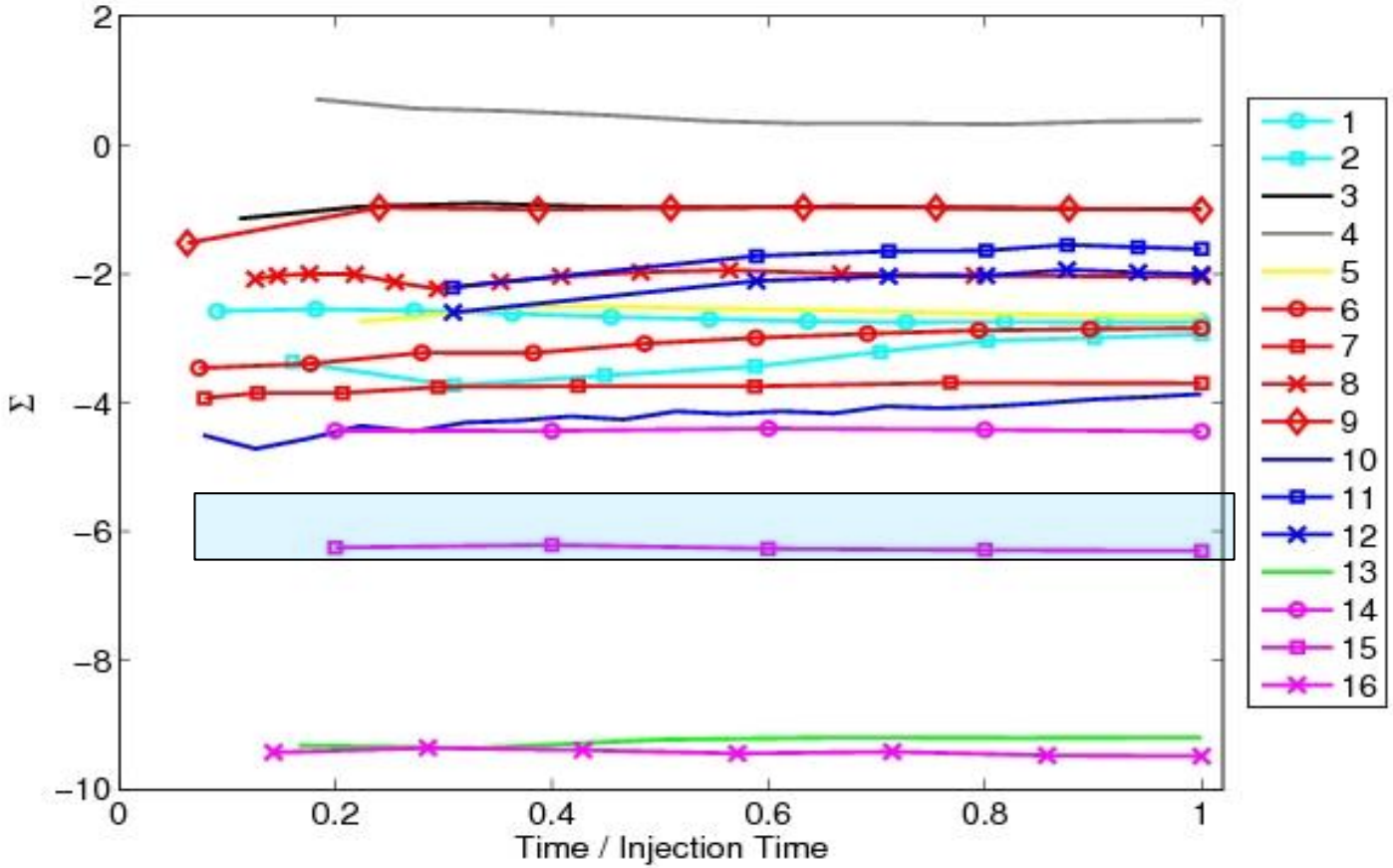
$$\log N_M(t) = a(t) - bM$$

$$\log N_M(t) = \Sigma + \log Q_{inject}(t) - bM$$

Seismogenic Index: Σ

Shapiro et al, 2007 (GRL);
Shapiro et al, 2010 (The Leading Edge)

Σ at various sites + Groningen



1-2: Ogachi 1991/93, **3**: Cooper Basin 2003, **4**: Basel 2006, **5**: Paradox Valley, **6-9**: Soultz 1996/95/93/00. **10-12**: KTB 2005/94.**13**: Barnett Shale, **14-16**: Cotton Valley stages A, B,C.

Modified from (Dinske & Shapiro, 2013)

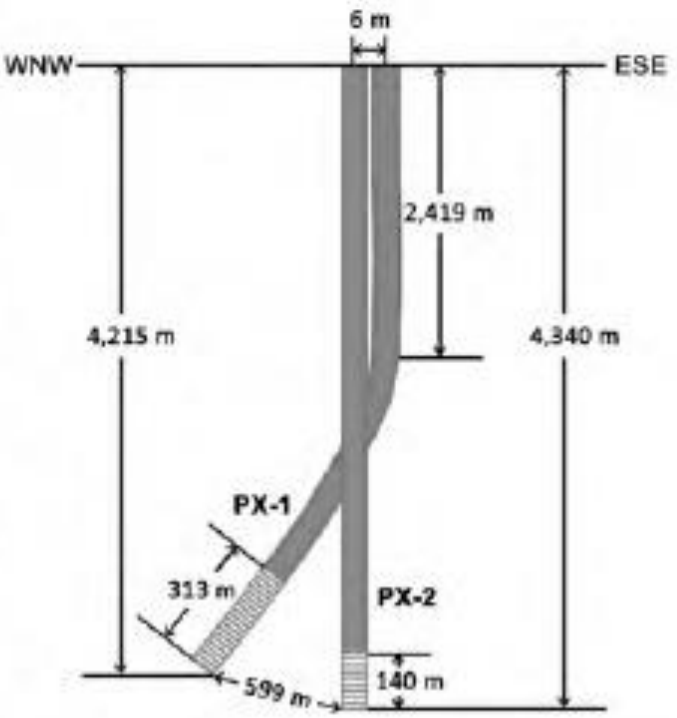


Figure O-1. Pohang EGS location and the schematics of the two exploration wells PX-1 and PX-2.

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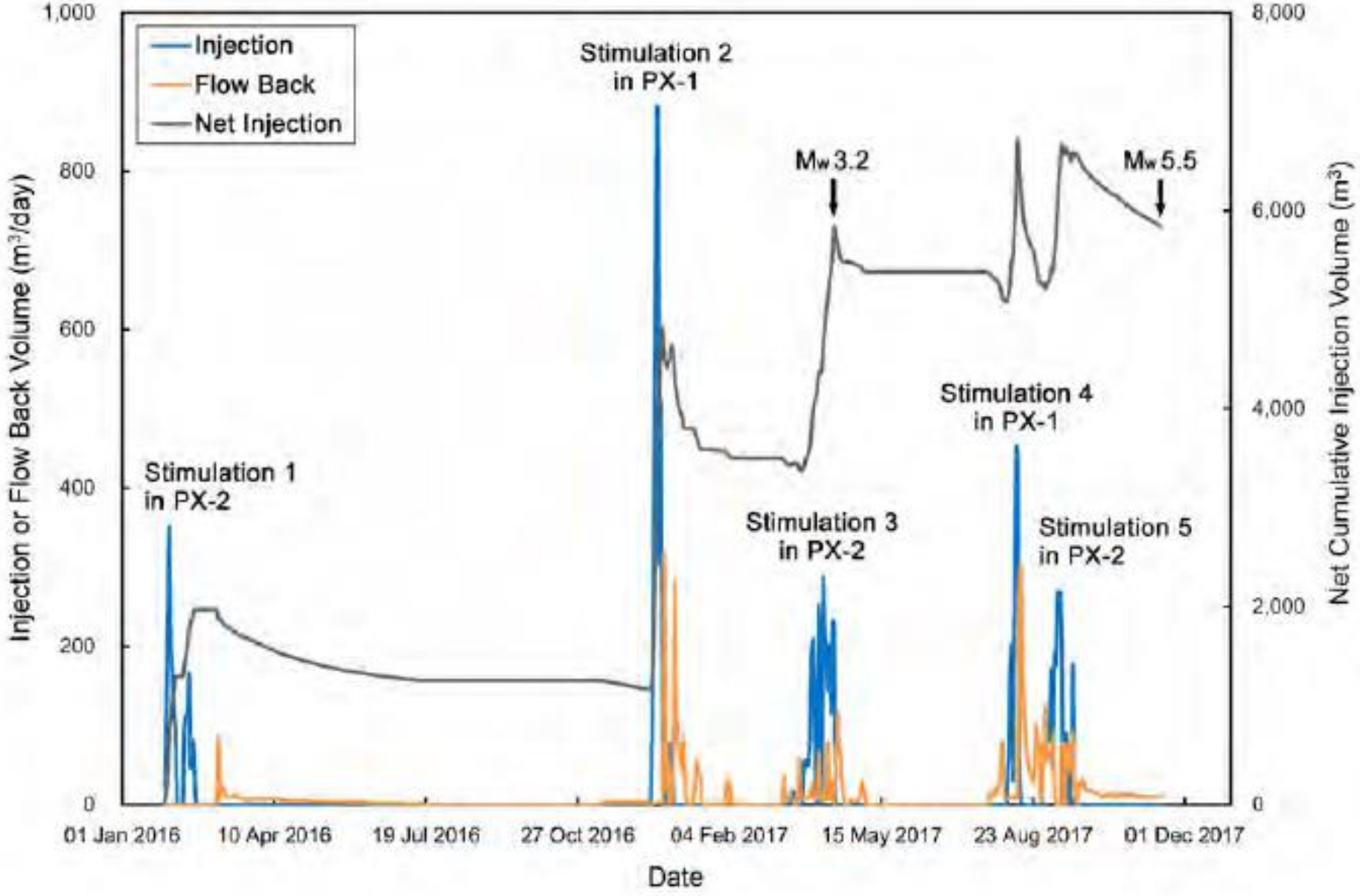

Fig. 1-2. Injection, flow back and net injection volumes during five hydraulic stimulations conducted at PX-1 and PX-2 geothermal wells.

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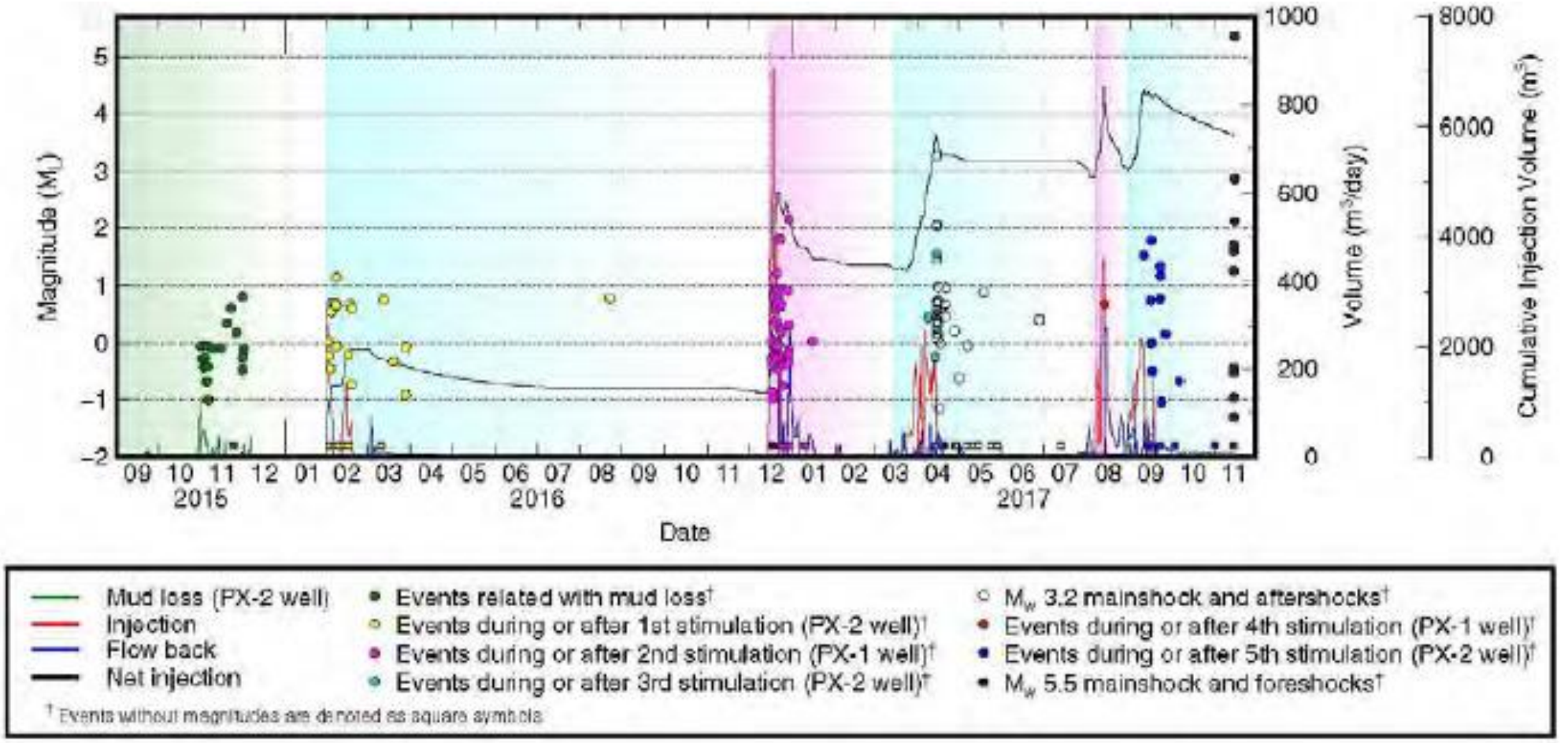

Fig. A-4-2. Temporal distribution of EGS project activity and seismicity of events whose magnitude was determined.

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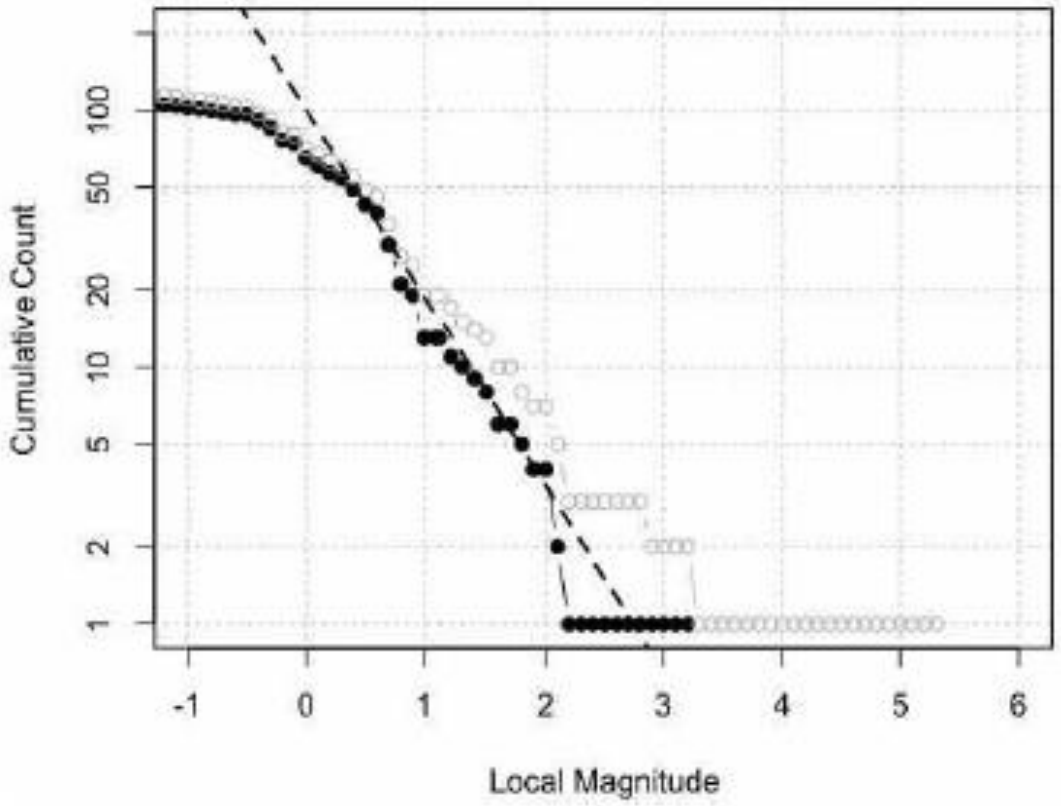

Figure O-12. Gutenberg-Richter magnitude frequency diagram. Solid symbols correspond to earthquakes occurring during or following the five well stimulations at the Pohang EGS facility. The dashed line has the formula $\log_{10}(N) = 2.0 - 0.73\ M_L$ and was determined using the method of *Tinti and Mulargia* [1985]. Open symbols include foreshocks, mainshock and stimulation events.

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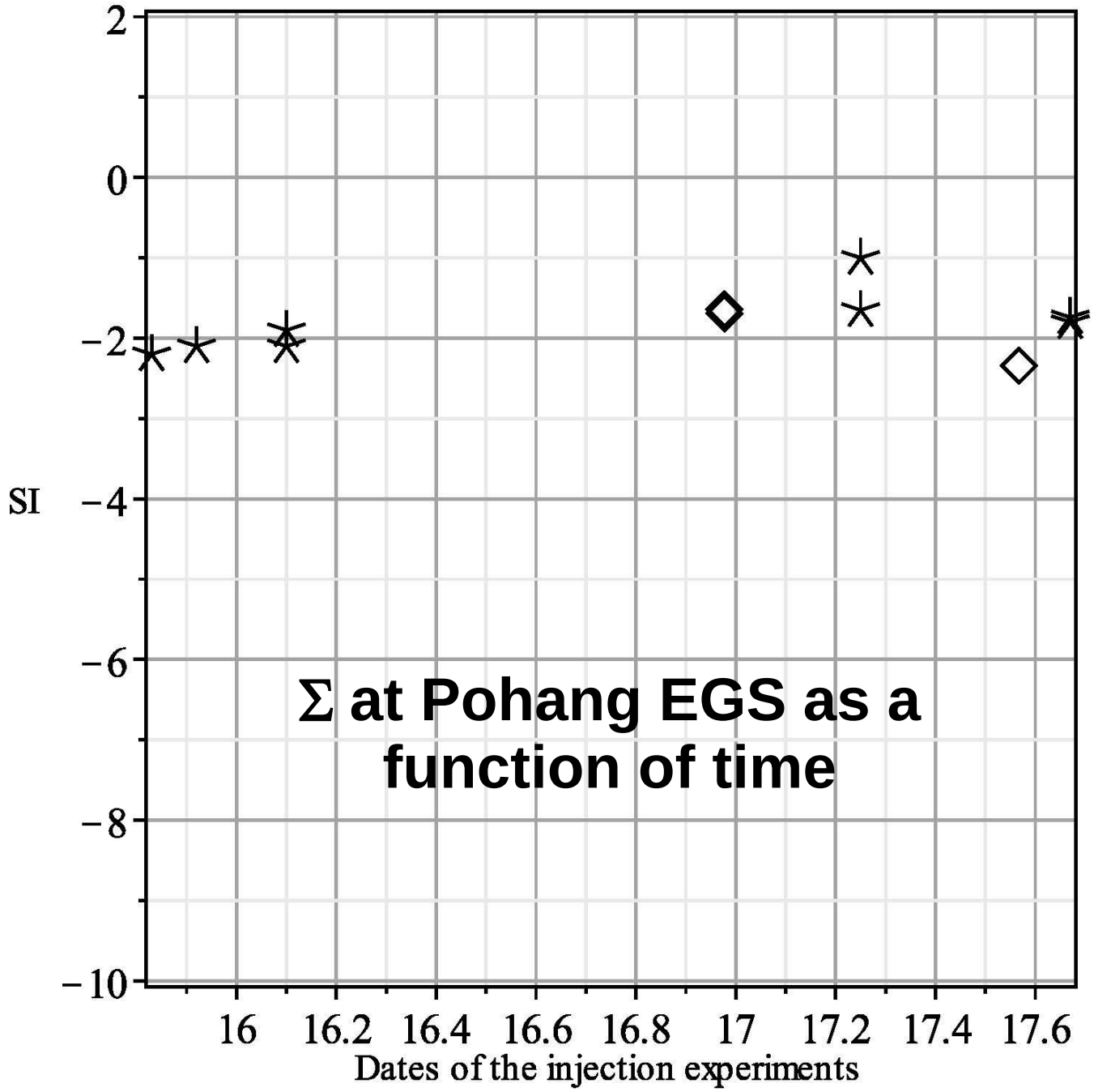
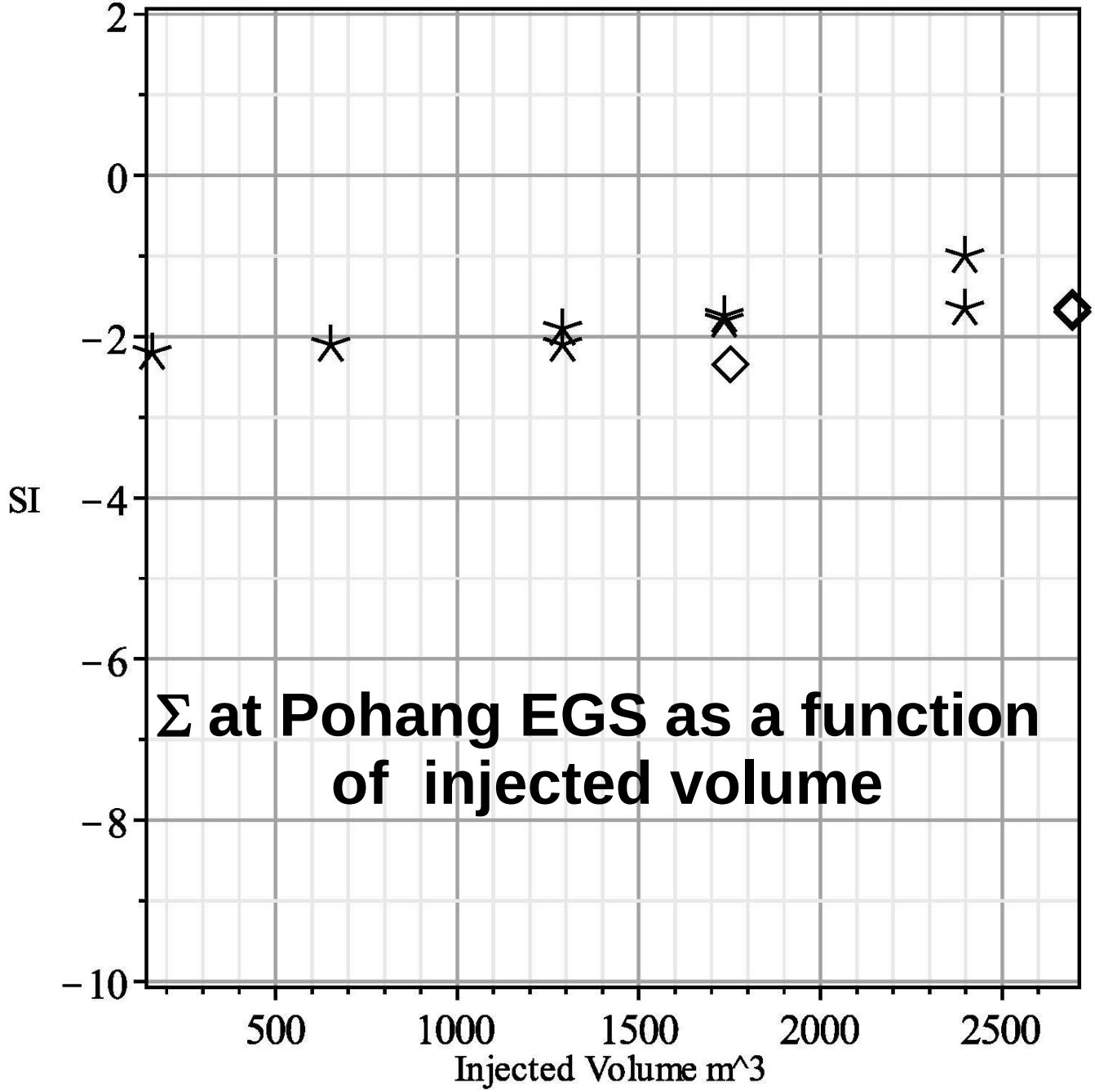
Simplifying Assumptions

- An effective homogeneous infinite porous continuum.
- Monotonic independent injections.
- A complete recharge during the time periods between injections.
- Triggering by pore pressure.

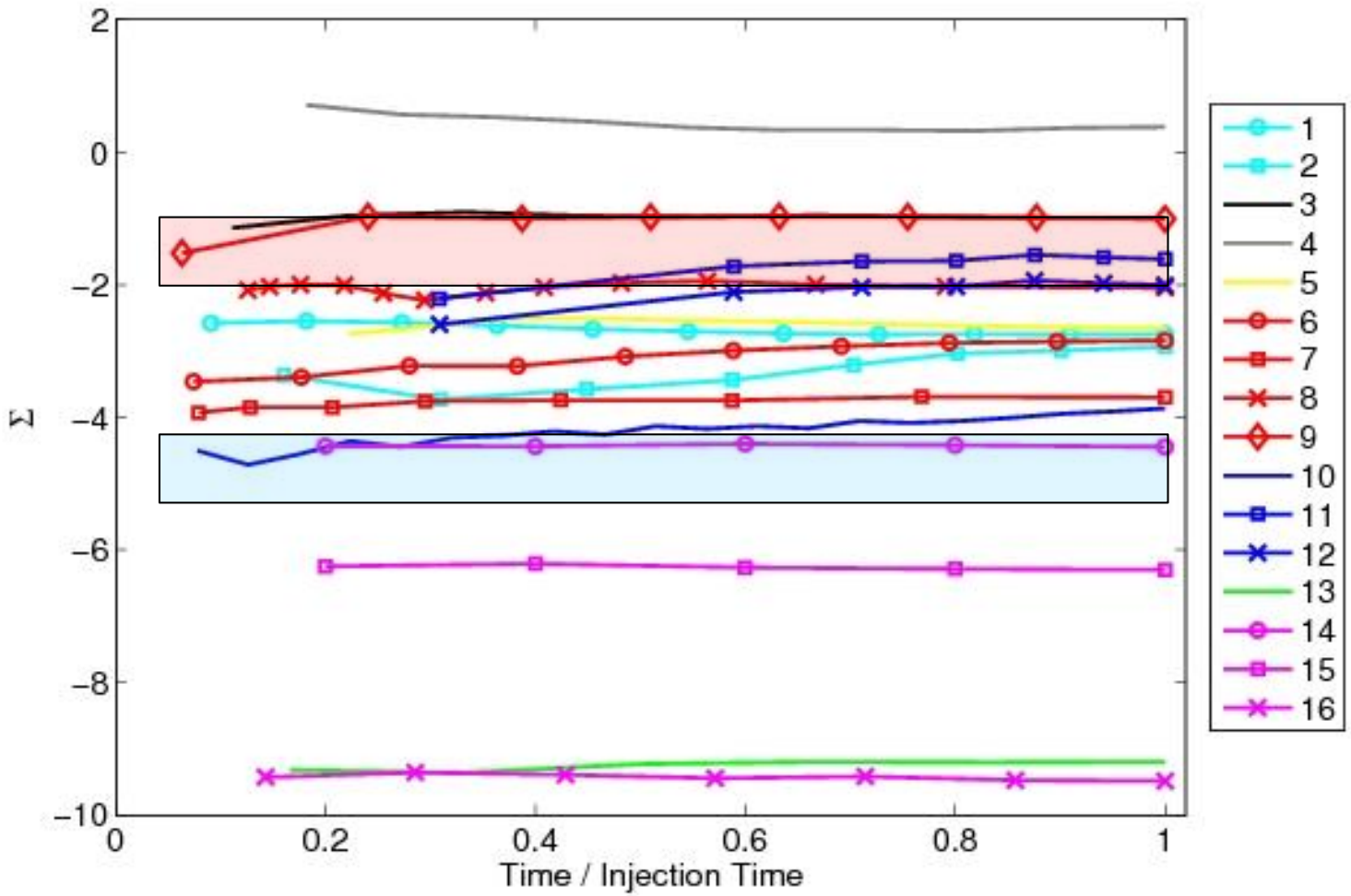

2
0
−2
−4
−6
−8
−10
SI
16
16.2
16.4
16.6
16.8
17
17.2
17.4
17.6
Dates of the injection experiments
Σ at Pohang EGS as a function of time


2
0
−2
−4
−6
−8
−10
SI
500
1000
1500
2000
2500
Injected Volume m^3
Σ at Pohang EGS as a function of injected volume

Σ at various sites

Pohang

Groningen



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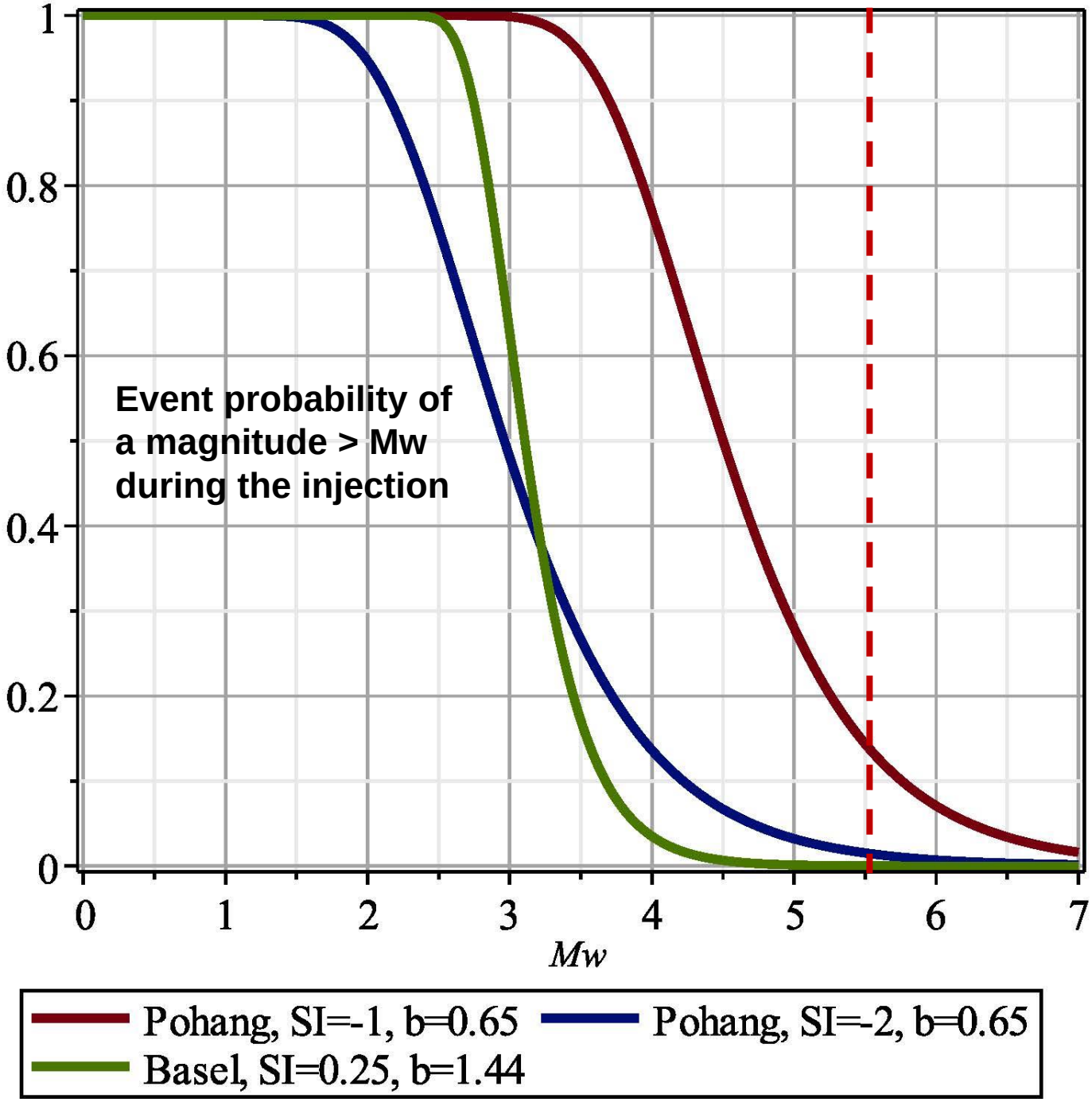
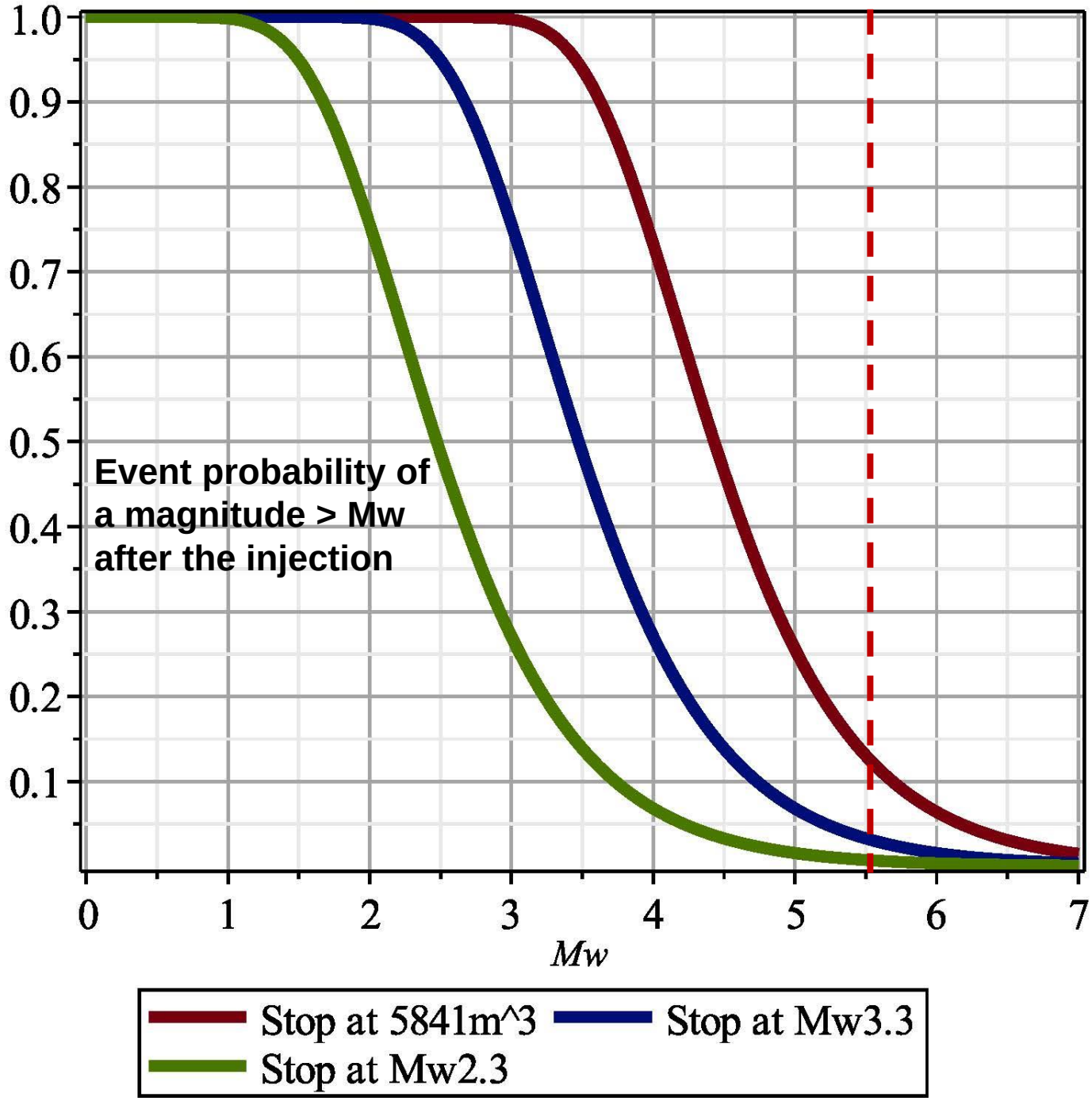
Poisson Process: Event Probability

$$W_{ev \geq M} = 1 - exp[-N_M]$$

$$W_{ev \geq Mmax} = 1 - exp[-1] \approx 0.63$$

$$W_{ev \geq M} = 1 - exp[-V_f(t)10^{\Sigma - bM}]$$


1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
Mw
Event probability of
a magnitude > Mw
during the injection
Pohang, SI=-1, b=0.65
Pohang, SI=-2, b=0.65
Basel, SI=0.25, b=1.44


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Event probability of
a magnitude > Mw
after the injection
0
1
2
3
4
5
6
7
Mw
Stop at 5841m^3
Stop at Mw3.3
Stop at Mw2.3

Conclusions

The seismogenic index, Σ, of the Pohang site is approximately between -2 and -1. During the stimulation, we observe a tendency of Σ to increase with time: possibly an indication of a gradual stimulation of seismically more active zones.

The event of Mw3.3 on April 15th of 2017 indicated a jump of Σ to -1.

Our estimate of the probability of the Pohang earthquake is approximately 15%.

One of decisive factors was the low b value. A combination of a low b-value and a rather high seismogenic index made the probability of the Mw5.5 event significant.

A termination of all injection operations after the Mw3.3 event would reduce the probability of an Mw5.5 event down to approximately 3%. Their termination at Mw2.3 would reduce it down to approximately 1%.

A real-time seismic monitoring permitting a precise 3-D event location and an estimating of the temporal evolutions of the stimulated volume geometry and of the seismogenic index could potentially help to prevent or to delay the occurrence of such an earthquake.