A Correlation Analysis Between Injection Rates And Magnitude Distribution In The Geysers Geothermal Field.

Konstantinos Michail Leptokaropoulos
Polish Academy of Sciences

Monika Staszek
Polish Academy of Sciences

Correlation analysis between injection rates and magnitude distribution in The Geysers Geothermal Field

Konstantinos Leptokaropoulos[1], Monika Staszek[1], and Szymon Cielesta[1]

[1]Department of Seismology, Institute of Geophysics, Polish Academy of Sciences, K. Janusza 64, 01 452 Warsaw, Poland, kleptoka@igf.edu.pl,

Summary

By definition, hydraulic fracturing involves high-pressure injection of fluid into a well in order to create new cracks and enhance permeability for sustainable exploitation of oil, gas and geothermal energy. The main aim of this study is to investigate the relation between seismic events magnitude distribution and fluid injection in the NW part of The Geysers geothermal site (California, USA). Various types of b-value analysis were performed in order to investigate thoroughly the impact of different parameters on magnitude distribution. Our main findings include:

- ✓ Distance from the open hole of Prati-9 injection well. The distances were selected in order to form datasets of almost identical size such that the b-value uncertainties are comparable. The differences in b-values are small and they do not indicate a significant b-value variation with the hypocentral distance from the open hole of the injection well (**Table 1**).
- ✓ Selected periods considered as stationary in terms of approximately constant seismicity rate. Based on the cumulative event occurrence plot (**Fig. 2**), the whole period that the catalog covers was divided visually into approximately stationary parts (Leptokaropoulos et al., 2018). In each of these parts we estimated the b-value and its standard deviation. It is shown in **Fig. 2** that the b-values vary from 0.85 to ~1.6, a quite large range considering the dimensions of the study area and the duration that data covers. No clear correlation can be obtained by such plot.
- ✓ Absolute injection rate values. No distinct connection between b-values and absolute injection rates could be observed under the current analysis (**Table 2**).
- ✓ Injection rates. In this approach a direct comparison between injection rates and the response of b-value is attempted (Leptokaropoulos and Staszek, 2018). The b-value is proportional to the slope of the injection rates (**Fig. 3**). Due to the relatively small available sample, we aggregated seismic activity within two time intervals of increasing and decreasing injection rate. A positive correlation with b-values was revealed, statistically significant at 0.01 level (**Fig. 4**). b-values were also calculated as a function of time lag from the injection activity. The magnitude distribution changes of induced events follow immediately or shortly (0-15 days time lag) after the injection rate changes (**Fig. 5)**.

Method

To estimate b-value in this study we applied the maximum likelihood estimator of Aki (1965) as follows:

$$\hat{b} = \frac{1}{\ln(10)\left[\langle M \rangle - (M_{\min} - \Delta M/2)\right]} \quad (1), \qquad \sigma_b = \frac{\hat{b}}{\sqrt{N}} \quad (2)$$

In equation 1$\langle M \rangle$ stands for the sample mean of the dataset, M_{min} is the completeness magnitude threshold and ΔM represents the values binning (round-off interval) of the reported magnitudes (Bender, 1983). The same author also provided the estimator of standard deviation of $\hat{b}$, σ_b, defined as (2), where N stands for the sample size. The asymptotic distribution of $\hat{b}$ is normal (N($\hat{b}$,σb)), and σ_b can be evaluated by (2), allowing for an adequate estimation of the confidence intervals of $\hat{b}$ for relatively large samples. We used this estimator for datasets with more than 100 samples, whereas for smaller datasets bootstrap confidence intervals were calculated instead. 10,000 realizations of random sampling with replacement were performed for each dataset. The confidence intervals were determined as the 0.159 and 0.841 quantiles, corresponding to one standard deviation assuming normal distributed random samples, an assumption that is valid based on the large number of realizations.

Data

We used an isolated cluster of seismicity located in the northwestern part of The Geysers geothermal field in the proximity of Prati-9 and Prati-29 injection wells. The cluster consisted of 1254 events which occurred between 10th of December 2007 and 23rd of August 2014 and were relocated by Kwiatek et al. (2015) from the original NCEDC catalogue so that the relative hypocentral error did not exceed 50m. In this study we used 1121 events from this cluster which form a dinstinct cloud occurred up to the maximum distance of 600 m from Prati-9 (**Fig. 1a**). The dataset includes events with magnitudes from 1.4 to 3.2 (**Fig. 1b**). The completeness magnitude estimated by Kwiatek et al. (2015) equals 1.37. Injection activity in Prati-9 well was carried on continously during the analyzed time period, whereas injection into Prati-29 took place between April 2010 and June 2013 (**Fig. 1c**).

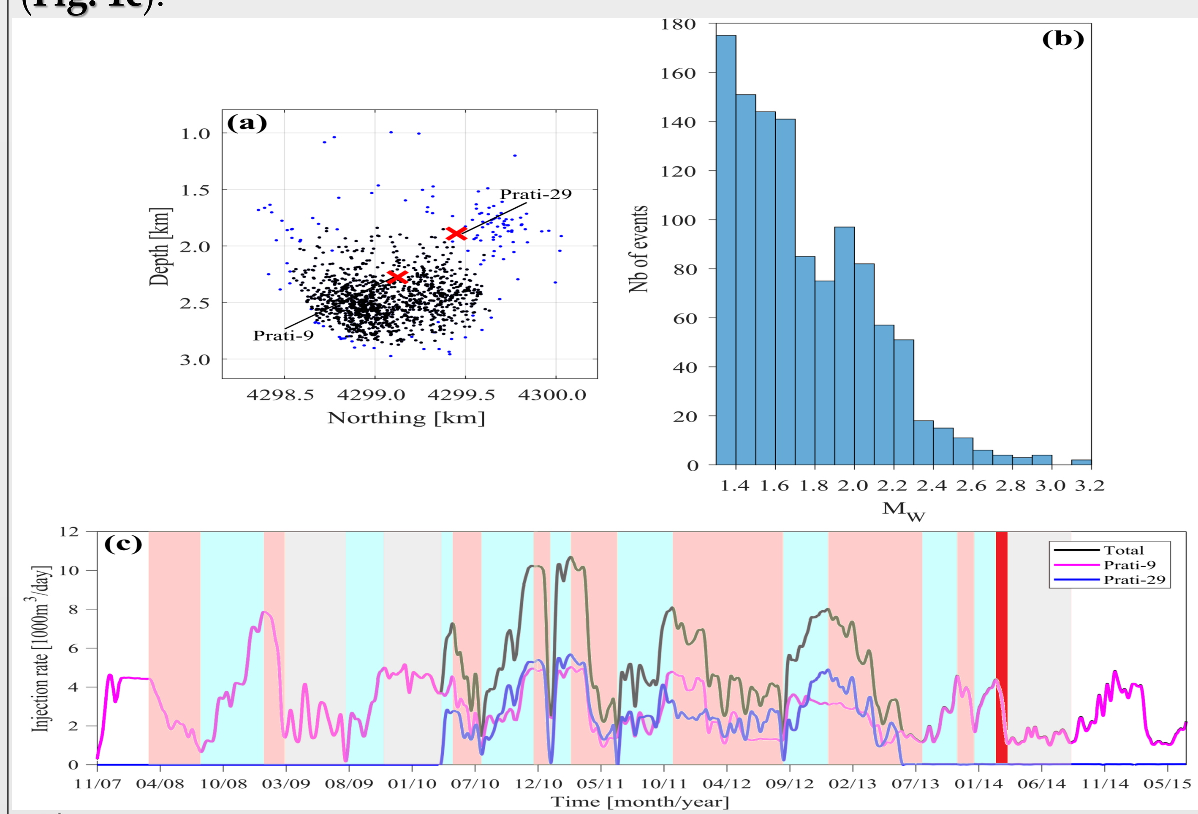

Fig. 1

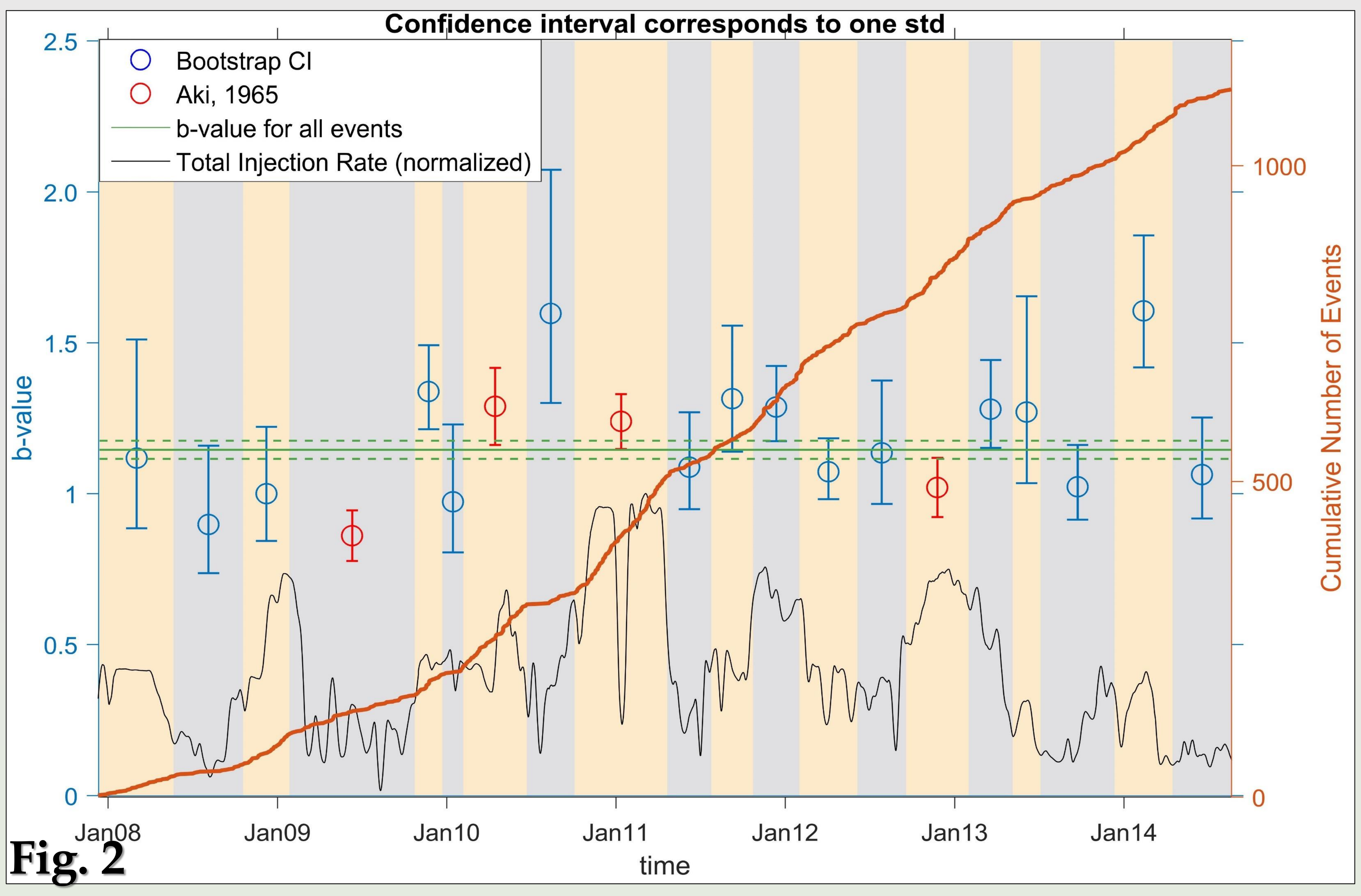

Fig. 2

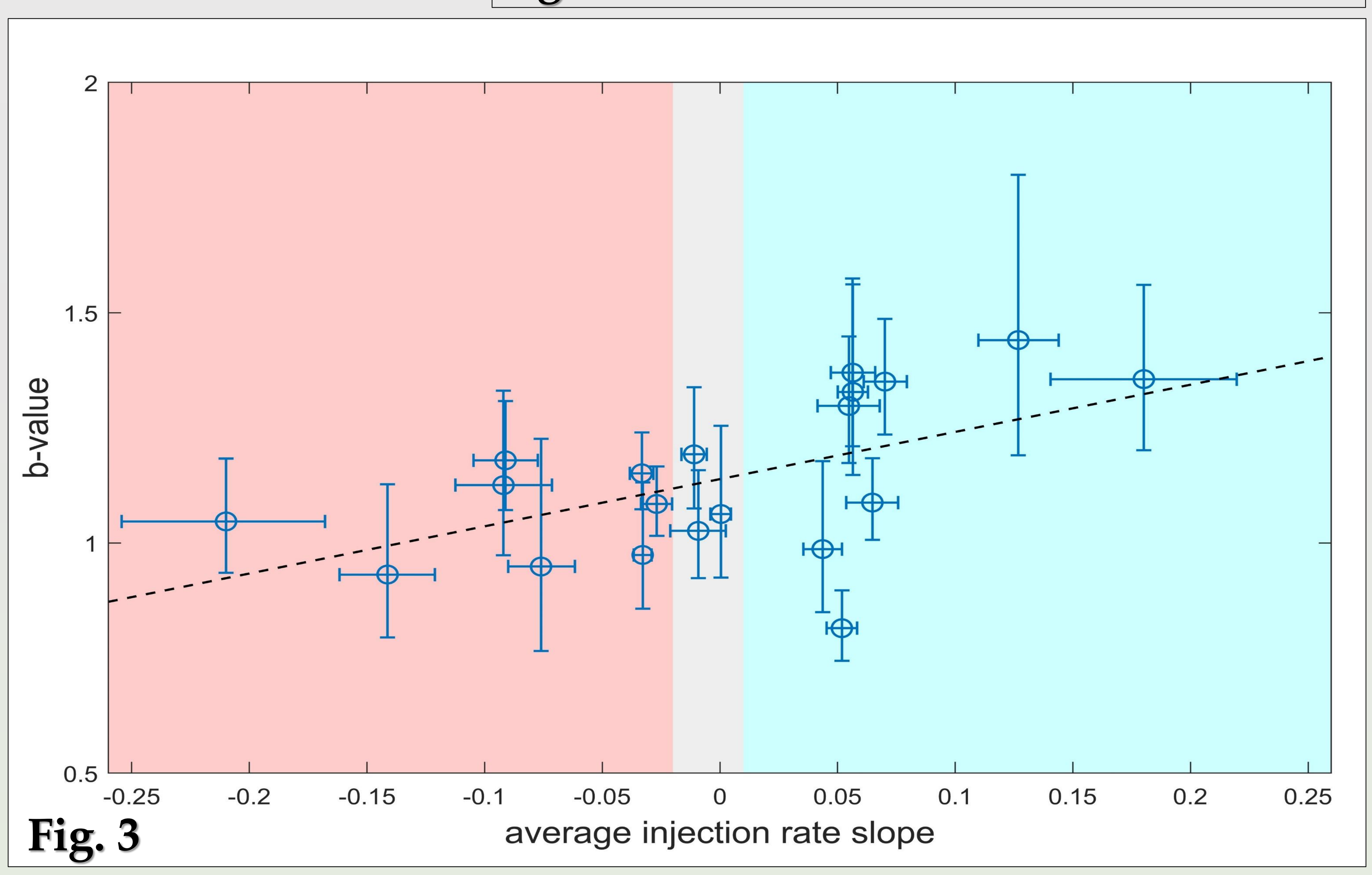

Fig. 3

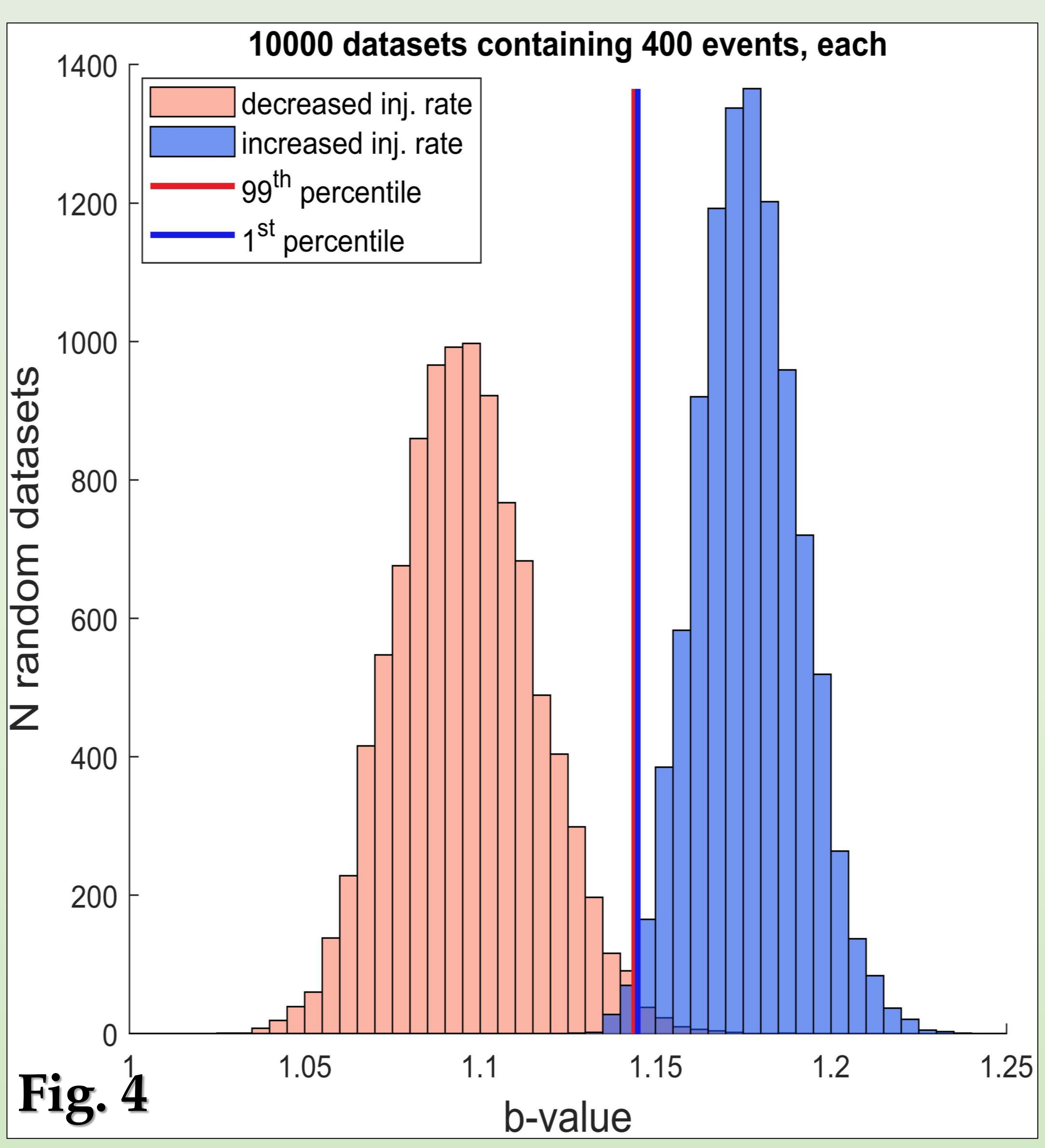

Fig. 4

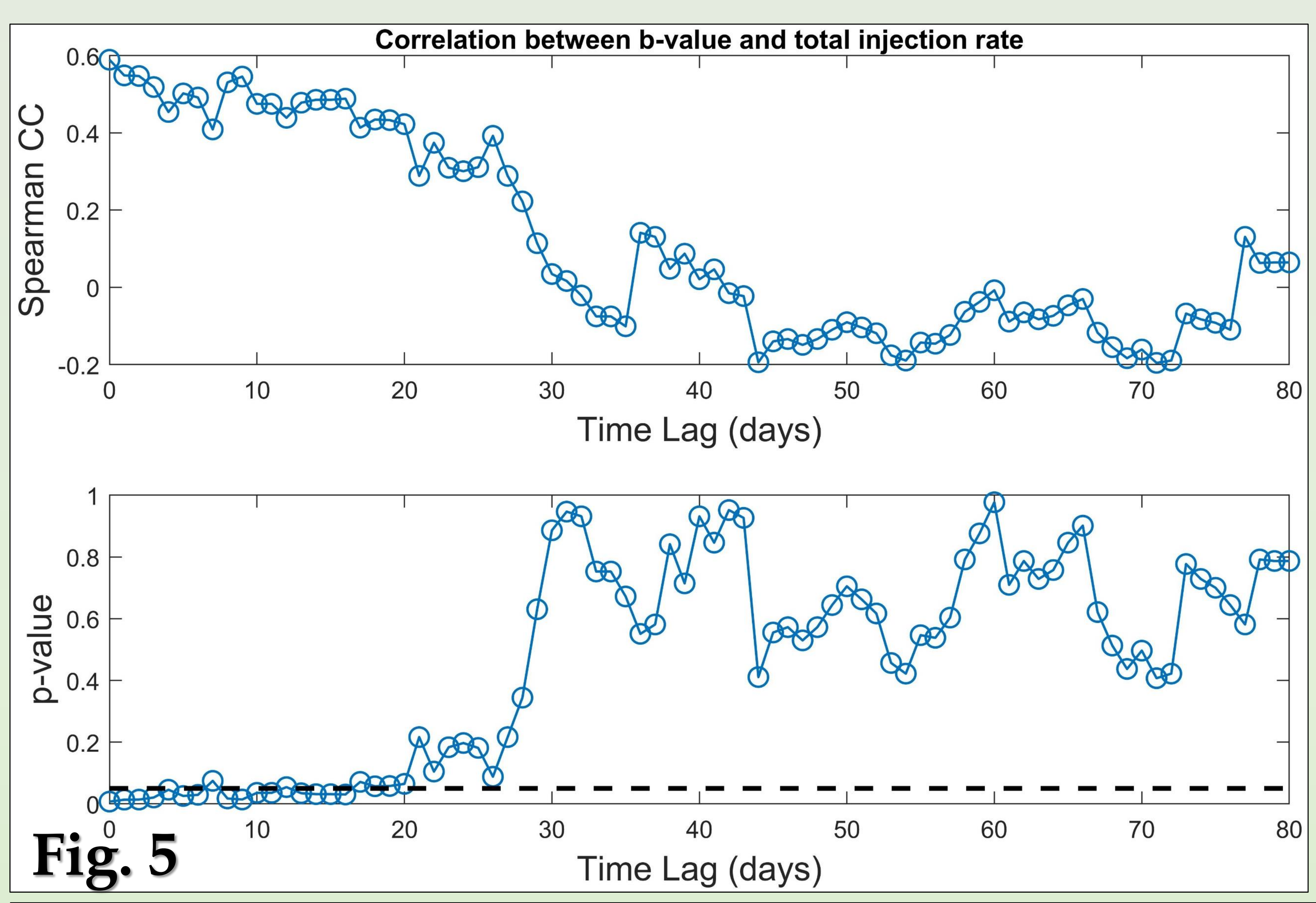

Fig. 5

Table 1

Distance from Prati-9	b-value
0-300m	1.17 ± 0.07 (282 events)
300-380m	1.12 ± 0.07 (282 events)
380-465m	1.12 ± 0.07 (278 events)
465-600m	1.16 ± 0.07 (279 events)

Table 2

Injection rate (m^3/day)	No of events	b-value	b-value within one σ
0 – 2,000	102	1.193	[1.087 - 1.322]
2,000 – 4,000	171	1.097	[1.029 - 1.176]
4,000 – 6,000	311	1.143	[1.089 – 1.201]
6,000 – 8,000	154	1.299	[1.211 – 1.403]
8,000 – 10,000	184	1.097	[1.036 – 1.165]
10,000 – 12,400	143	1.177	[1.102 – 1.261]

References

Aki, K. (1965) Maximum likelihood estimate of b in the formula logN = a − bM and its confidence limits. *Bull. Earthquake Res. Inst. Tokyo Univ.*, **43**, 237–239.

Bender, B. (1983) Maximum likelihood estimation of b-values for magnitude grouped data. *Bull. Seismol. Soc. Am.*, **73**, 831-851.

Kwiatek, G., Martínez-Garzón, P., Dresen, G., Bohnhoff, M., Sone, H., and Hartline, C. (2015) Effects of long-term fluid injection on induced seismicity parameters and maximum magnitude in northwestern part of the Geysers geothermal field. *J. Geophys. Res. Solid Earth*, **120**, doi:10.1002/2015JB012362.

Leptokaropoulos, K., Staszek, M., Lasocki, S., Martínez-Garzón, P., and Kwiatek, G. (2018) Evolution of seismicity and its connection to stimulation processes, in North-western Geysers Geothermal field. *Geophys J. Int.*, DOI: 10.1093/gji/ggx481.

Leptokaropoulos, K., and M. Staszek (2018), Temporal response of magnitude distribution to fluid injection rates in The Geysers Geothermal Field, *Acta Geophys.* (Manuscript Under Preparation for special issue on SHEER).

EAGE EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

8th7EAGE Workshop on Passive Seismic, 26-29 March, **2018**, Krakow, Poland

SHale gas Exploration and Exploitation induced Risks

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 640896.

Acknowledgements

This work was supported within SHEER: "SHale gas Exploration and Exploitation induced Risks" project funded from the European Union Horizon 2020 – Research and Innovation Programme, under grant agreement 640896.
The work was also partially supported within statutory activities No 3841/E-41/S/2018 of the Ministry of Science and Higher Education of Poland,.