Probabilistic properties of injection induced seismicity – implications for the seismic hazard analysis

Conference Paper · April 2017

4 authors:

Stanislaw Lasocki
Polish Academy of Sciences

Paweł Urban
Polish Academy of Sciences

Grzegorz Kwiatek
Helmholtz-Zentrum Potsdam - Deutsches Ge…

Patricia Martínez-Garzón
Helmholtz-Zentrum Potsdam - Deutsches Ge…

Institute of Geophysics
Polish Academy of Sciences

Probabilistic properties of injection induced seismicity – implications for the seismic hazard analysis

Stanisław LASOCKI [(1)], Paweł URBAN [(1)], Grzegorz KWIATEK [(2)] and Particia MARTINEZ-GARZÓN [(2)]

(1) Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland; (2) Helmholtz-Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany

EGU2017-3019

INTRODUCTION

Injection induced seismicity (**IIS**) is an undesired dynamic rockmass response to massive fluid injections. This includes reactions, among others, to hydro-fracturing for shale gas exploitation. Complexity and changeability of technological factors that induce IIS, may result in significant deviations of the observed distributions of seismic process parameters from the models, which perform well in natural, tectonic seismic processes. The aim of this work is attempt to answer to the following questions:

- Do IIS earthquakes follow the Gutenberg-Richter distribution law, so that the magnitude distribution can be modelled by an exponential distribution? If not, than how can we model this distribution?
- Is the occurrence process of IIS earthquakes Poissonian? Is it segmentally Poissonian? If yes, how are these segments linked to cycles of technological operations? If it is neither Poissonian nor segmentally Poissonian, then what options do we have to model the occurrence process?

METHOD OF ANALYSIS

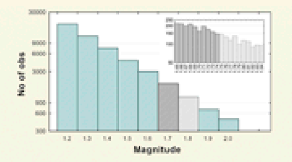
Two empirical distributions have been analyzed:
· *distribution of **magnitude (M)*** and
· *distribution of **interevent times (τ)***

I step (for *M* and *τ* distribution):
Test conformity of *M* and *τ* distributions with the exponential distribution. The initial null hypothesis is:
H_{01}: the distribution of the tested parameter is an exponential distribution

II step (for *M* distribution):
If the H_{01} is rejected in case of *M* distribution, we study complexity of the *M* distribution by means of the tests for multimodality (Silverman, 1986; Efron and Tibshirani, 1993). We test two null hypotheses:
H_{02}^{1} – **multimodality**: the probability density of *M* is unimodal
H_{02}^{2} – **multi-bump**: the probability density of *M* has one bump to the right of the mode
Details on the testing procedure, when applied to the exponential-like *M* distribution, are presented in Lasocki and Papadimitriou (2006).

II step (for *τ* distribution):
If the H_{01} is rejected in case of *τ* distribution, we study the Weibull distribution as the next option to model this distribution. Hence, we test the null hypothesis:
H_{03}: the *distribution of τ is a Weibull distribution.*

We test H_{01} and H_{03} hypothesis by means of the Anderson-Darling (A-D) test (Marsaglia and Marsaglia, 2004) at the significance level 0.05. The A-D test is applicable only to continuous variables. Due to that we randomize each *M* within its round off interval by transforming according to the formula presented in Lasocki and Papadimitriou (2006).



References:
- Efron, B., and Tibshirani R.J. (1993) An Introduction to the Bootstrap. CRC Press, Boca Raton, Fla.
- Kwiatek, G., P. Martinez-Garzon, G. Dresen, M. Bohnhoff, H. Sone and C. Hartline (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.
- Lasocki, S. and Papadimitriou, E.E. (2006) Magnitude distribution complexity revealed in seismicity from Greece. J. Geophys. Res. 111, B11309, doi: 10.1029/2005JB003794
- Leptokaropoulos, K. M., Karakostas, V. G., Papadimitriou, E. E., Adamaki, A. K., Tan, O. and Inan, S. (2013) A homogeneous earthquake catalog for Western Turkey and magnitude of completeness determination. Bull Seismol Soc Am 103 (5), 2739-2751.
- Marsaglia, G., and J. Marsaglia (2004) Evaluating the Anderson-Darling distribution. J Stat. Soft. 9, 1-5,
- Martinez-Garzon, P., G. Kwiatek, H. Sone, M. Bohnhoff, G. Dresen, and C. Hartline (2014), Spatiotemporal changes, faulting regimes, and source parameters of induced seismicity: A case study from The Geysers geothermal field. J. Geophys. Res. Solid Earth, 119, 8378-8396.
- Silverman, B.W., (1986) Density Estimation for Statistics and Data Analysis. CRC press, Boa Raton, Fla.

ACKNOWLEDGEMENTS: This work was supported within SHEER: "Shale Gas Exploration and Exploitation Induced Risks" project funded from Horizon 2020 – R&I Framework Programme, call H2020-LCE 16-2014-1 and within statutory activities No3841/E-41/S/2016 of Ministry of Science and Higher Education of Poland.

STUDIED CASES

We have analyzed two groups of data from the compiled SHEER database, namely Oklahoma and The Geysers data. Both groups are unique datasets from well-studied IIS cases, linked to shale gas operations.

OKLAHOMA

The Oklahoma seismicity is induced by two technological processes: hydrofracturing and wastewater injection, which is carried on into hundreds of injection wells (Fig.1). We analyse the seismic catalogue comprising 2674 events from 01/01/2010 - 31/12/2014. The strongest event had M_L 4.7. Using the "Completeness Magnitude Estimation" application (Leptokaropoulos et al., 2013) of the IS-EPOS Platform for Anthropogenic Seismicity Research (*tcs-ah.epos.eu*), it has been established at 90% level of significance that the catalogue is complete starting from magnitude $M_{min} = 2.5$. The complete part of catalogue comprises 2309 events. The rate of activity is presented on Fig. 2.

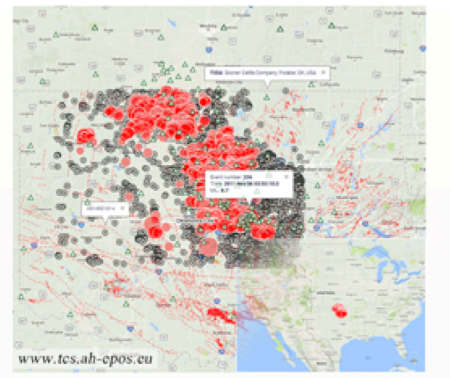


Fig.1 Location of injection wells (black circles), seismic events (red circles), seismic stations (green triangle) and faults (red lines).

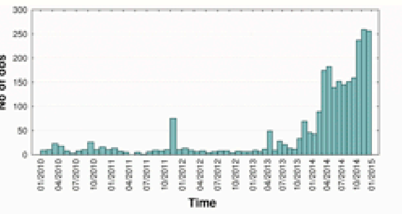


Fig.2. Seismic activity plot in 1-month bins.

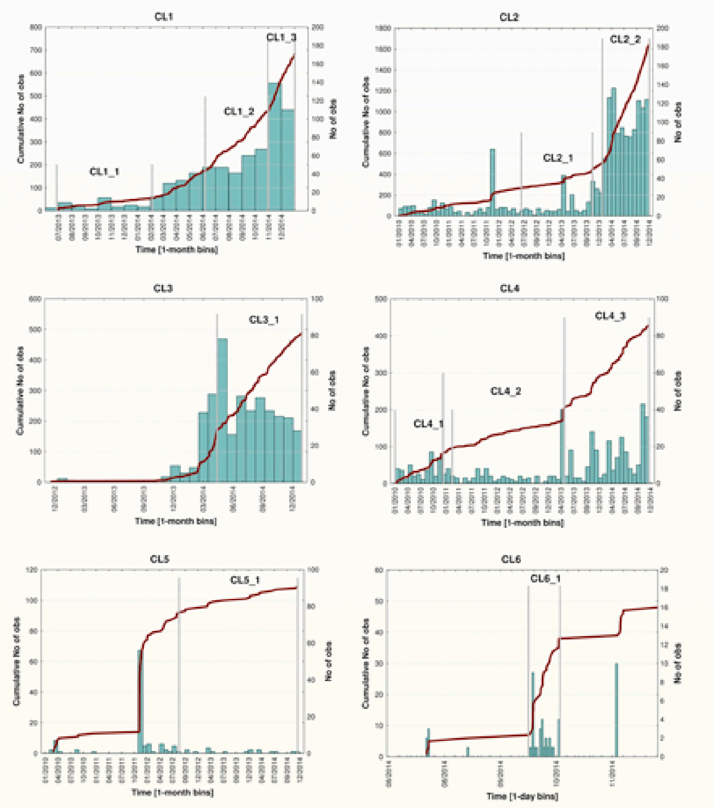


Fig.4 Cumulative activity plot (red line) and seismic activity rate (bins) - clusters CL1-CL6

I stage of analysis: six spatial clusters **CL1, CL2 (CL3, CL4, CL5) and CL6** have been extracted - Fig. 3. Basic information about the selected clusters of seismicity is provided in Table 1.

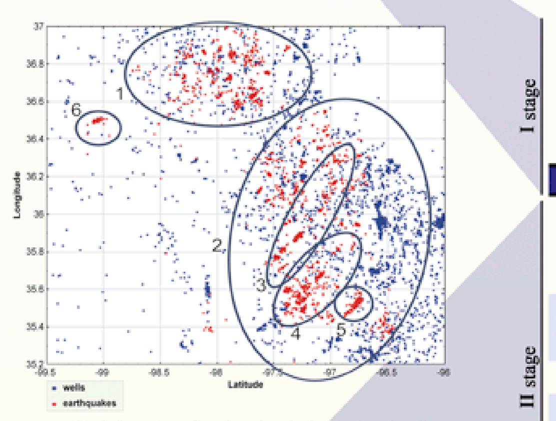


Fig.3. Location of earthquakes (red points) and wells (blue points). Ellipses enclose events that form the further analyzed clusters of seismicity.

II stage of analysis: Extract from the clusters series of events such that the activity rate was more or less constant within each of these series (Fig. 4). The selected series are presented in Table 1.

Stage	Event series	Cluster	Activity period	N	λ [1/day]	Largest M
I stage		CL1	14/07/2010 – 31/12/2014	672	0.41	4.3
		CL2	01/01/2010 – 30/12/2014	1568	0.86	4.7
		CL3	20/11/2012 – 30/12/2014	483	0.63	4.2
		CL4	01/01/2010 – 19/12/2014	387	0.21	4.5
		CL5	22/02/2010 – 15/12/2014	98	0.06	4.7
		CL6	21/08/2014 – 22/12/2014	48	0.39	3.9
II stage	CL1_1	CL1	27/06/2013 – 02/02/2014	47	0.21	3.6
	CL1_2		07/06/2014 – 31/10/2014	257	1.76	4.3
	CL1_3		30/10/2014 – 31/12/2014	250	4.03	4.3
	CL2_1	CL2	13/06/2012 – 12/11/2013	161	0.31	4.4
	CL2_2		25/01/2014 – 30/12/2014	1122	3.31	4.3
	CL3_1	CL3	15/04/2014 – 30/12/2014	314	1.21	4.0
	CL4_1	CL4	01/01/2010 – 15/02/2011	78	0.19	4.2
	CL4_2		12/12/2010 – 25/04/2013	108	0.13	4.5
	CL4_3		27/04/2013 – 19/12/2014	214	0.36	4.5
	CL5_1	CL5	18/08/2012 – 15/12/2014	17	0.02	3.8
	CL6_1	CL6	15/10/2014 – 31/10/2014	32	2.00	3.8

Table1. Analyzed clusters of seismicity from Oklahoma dataset. N - number of events, λ - mean activity rate, Largest M - Largest magnitude in the cluster.

THE GEYSERS

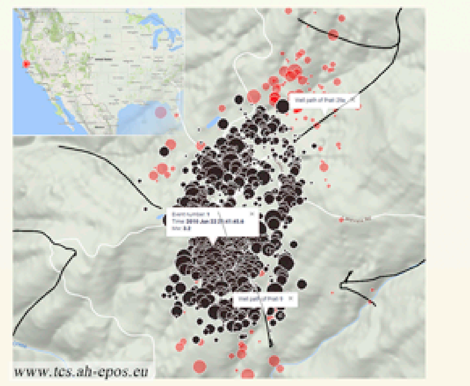


Fig.5. Distribution of seismicity at NW part of The Geysers. Black circles - analyzed events, black lines - well paths.

We use the part of The Geysers seismic and, which was processed to an extended catalog and made available for SHEER Consortium members by dr Grzegorz Kwiatek from GFZ. The seismicity cluster is localized in the NW part of The Geysers area (Fig. 5). The analyzed cluster consists of 1121 events, which occurred in the vicinity of Prati-9 and Prati-29 injection wells between 10/12/2007 and 20/08/2014. M_{min} determined by Kwiatek et al. (2015), is about 1.4.

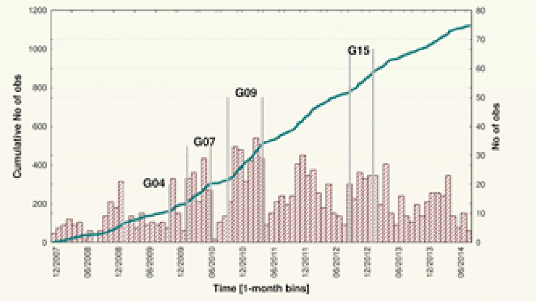


Fig.6. Cumulative activity plot (azure line) and seismic activity rate (bins) of the Geysers dataset.

I stage of analysis: The whole period of observation has been divided visually into consecutive constant activity rate periods. Four better populated periods have been analyzed: **G04, G07, G09, G15** - Fig.6 and Table 2.

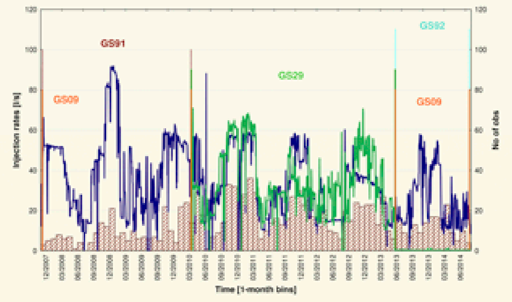


Fig.7. Seismic activity rate (red bins) and injection rates in wells Prati-9 (blue line) and Prati-29 (green line).

II stage of analysis: Clear correlation between seismic activity and injection operations in Prati-9 well and Prati 29 well has been demonstrated by Martinez-Garzon et al., 2014. To reduce possible influence of long-lasting changes of average injection rate we analyze 4 data samples (Fig. 7):
- **GS09** – events occurred when Prati-29 well was not operating,
- **GS29** – events occurred in the period in which both wells were operating,
- **GS91** – events had occurred before Prati-29 well began operating,
- **GS92** – events occurred after Prati-29 had stopped operating.

III stage of analysis: Investigation of the reaction of probabilistic distribution of seismic process parameters to short-term variations of injection rate. Whole period of observation has been divided into the days when an injection rate was higher than its median value and the days when an injection rate was lower than its median value (Fig. 8):
1. The injection rates of Prati-29 well - {**GI1_up, GI1_down**};
2. The injection rates of Prati-9 well in the period, in which Prati-29 well was operating - {**GI2_up, GI2_down**};
3. The summarized injection rates of both wells in the time period when Prati-29 was operating - {**GI3_up, GI3_down**};
4. The injection rates of Prati-9 well in the period before Prati-29 well began operating - {**GI4_up, GI4_down**};
5. The injection rates of Prati-9 well in the period after Prati-29 well stopped operating - {**GI5_up, GI5_down**}.

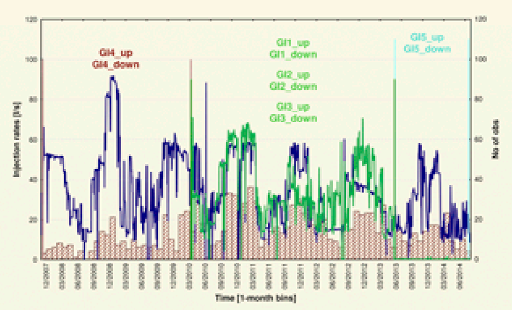


Fig.8. Seismic activity rate (red bins) and injection rates in wells Prati-9 (blue line) and Prati-29 (green line).

Stage	Event series	Activity period	N	λ [1/day]	Largest M
I stage	All data	10/12/2007 – 20/08/2014	1121	0.46	3.2
	G04	27/01/2009 – 24/10/2009	105	0.39	2.6
	G07	06/02/2010 – 23/06/2010	102	0.74	3.2
	G09	04/10/2010 – 22/04/2011	185	0.93	2.7
	G15	18/09/2012 – 31/01/2013	108	0.80	2.6
II stage	GS09	10/12/2007 – 10/04/2010 & 22/06/2013 – 20/08/2014	420	0.33	3.1
	GS29	11/04/2010 – 21/06/2013	701	0.60	3.2
	GS91	10/12/2007 – 10/04/2010	248	0.29	2.7
	GS92	22/06/2013 – 20/08/2014	172	0.40	3.1
III stage	GI1_down	11/04/2010 – 21/06/2013	260	0.46	3.2
	GI2_up	11/04/2010 – 21/06/2013	455	0.82	2.7
	GI2_down		234	0.43	3.2
	GI3_up	11/04/2010 – 21/06/2013	461	0.82	2.7
	GI3_down		231	0.40	3.2
	GI4_up	10/12/2007 – 10/04/2010	172	0.42	2.7
	GI4_down		71	0.17	2.6
	GI5_up	22/06/2013 – 20/08/2014	86	0.48	3.1
	GI5_down		78	0.43	3.0

Table 2 Analyzed series of seismicity from the Geysers dataset. N - number of events, λ - mean activity rate, Largest M - Largest magnitude in the event series.

RESULTS

OKLAHOMA

Table 3 contains results of testing the null hypothesis for distribution of *M* and *τ*.

I stage of analysis: $H_{01}(M)$ is rejected highly confidently in the whole dataset as well as in four out of six clusters.

II stage of analysis: $H_{01}(M)$ is not rejected in 9 out of 11 stationary series of seismic events. It suggests that the rejection for clusters from I stage of analysis may be due to time variation of the *M* distribution, which might stabilize in the stationary series of events.

Although statistically significant, the deviations of the actual *M* distributions from the best fitted exponential distributions are not big. The tests for multimodality **do not reject** the subsequent two null hypotheses:
$H_{02}^{1}(M)$ and $H_{02}^{2}(M)$.

As an example, Fig. 9 presents the differences between CDF's for the series CL1_2. One can see in the figure that in a range of larger magnitudes the exponential distribution model underestimates distinctly the actual values of CDF. This feature could have a significant negative impact on the accuracy of hazard estimates, if these estimates were based on such an exponential model of *M* distribution. The nonparametric CDF estimates very well fit to the empirical CDF. It is clear, that the use of non-parametric, kernel estimators of *M* distribution prevails over the use of exponential distribution model for the seismicity data from Oklahoma dataset.

«««« *M* distribution (τ) distribution »»»»

Stage	$H_{01}(M)$ Exponential distribution: Test p-value	G-R b-value	β	Largest M	N	Analyzed dataset		N	$H_{01}(τ)$ Exponential distribution: λ [1/day]	Test p-value	$H_{03}(τ)$ Weibull distribution: 1/λ	α	Test p-value
	<0.0001	0.99	2.28	4.7	2309	The whole catalog		2308	1.31	<0.0001	3.07	0.52	<0.0001
I stage	0.007	1.09	2.51	4.3	672	CL1	Clusters of seismicity	671	0.42	<0.0001	1.82	0.51	<0.0001
	0.001	0.95	2.19	4.7	1568	CL2		1567	0.9	<0.0001	1.91	0.52	<0.0001
	0.011	1.04	2.39	4.2	483	CL3		482	0.63	<0.0001	1.55	0.54	0.120
	0.089	0.88	2.02	4.5	387	CL4		386	0.24	<0.0001	0.41	0.53	0.247
	0.006	0.55	1.26	4.7	98	CL5		97	0.06	<0.0001	0.31	0.35	0.293
	0.921	1.01	2.32	3.9	48	CL6		47	0.38	<0.0001	1.26	0.45	0.180
II stage	0.114	1.03	2.37	3.6	47	CL1_1	Series from cluster CL1	46	0.22	0.001	0.32	0.58	0.624
	0.065	1.02	2.35	4.3	257	CL1_2		256	1.79	<0.0001	2.13	0.75	0.928
	0.397	1.18	2.72	4.3	250	CL1_3		249	4.03	0.020	4.44	0.83	0.777
	0.037	0.88	2.02	4.4	161	CL2_1	Series from cluster CL2	160	0.35	<0.0001	0.64	0.5	0.360
	0.003	1.10	2.52	4.3	1122	CL2_2		1121	3.34	<0.0001	3.93	0.76	0.875
	0.074	1.10	2.52	4.0	314	CL3_1	A series from cluster CL3	313	1.22	<0.0001	1.52	0.7	0.383
	0.141	0.68	1.57	4.2	78	CL4_1	Series from cluster CL4	77	0.23	<0.0001	0.35	0.56	0.394
	0.702	0.86	1.97	4.5	108	CL4_2		107	0.14	<0.0001	0.27	0.47	0.091
	0.319	1.00	2.30	4.5	214	CL4_3		213	0.37	<0.0001	0.55	0.59	0.809
	0.939	0.93	2.14	3.8	17	CL5_1	A series from cluster CL5	16	0.02	0.380	0.02	0.71	0.615
	0.851	0.97	2.22	3.8	32	CL6_1	A series from cluster CL6	31	1.94	0.025	2.45	0.68	0.784

Table 3. Results of tests for exponentiality of magnitude (M) distribution and goodness-of-fit tests of exponential and Weibull distributions for interevent time (τ) of the Oklahoma data. The sets, in which the null hypothesis has been rejected at the significance level 0.05, are given in bold red. β - distribution parameter, Largest M - largest magnitude in the sample, λ - mean event rate, 1/λ - scale parameter, α - shape parameter.

I and II stage of analysis: $H_{01}(τ)$ is rejected highly significantly for all but one studied datasets. The not rejecting result of the test is likely due to the non-representativeness of the sample (16 data points) rather than due to the conformity of the population distribution of *τ* with the exponential distribution. $H_{03}(τ)$ is not rejected in most of the considered datasets. The only exceptions are bigger datasets: the whole dataset and the big clusters CL1 and CL2. It may be speculated that such big datasets comprise mixtures of data from different seismicity generation processes, each having different Weibull distribution of *τ*.

The CDF's of *τ* in the series CL1_2 are shown in Fig. 10. The CDF from the exponential model strongly deviates from the actual data. As can be expected, the kernel estimate models the observations very well. It is better than the CDF from the Weibull model, but the latter seems to be sufficient. The occurrence process of Oklahoma seismicity can be represented by a Weibull distribution model.

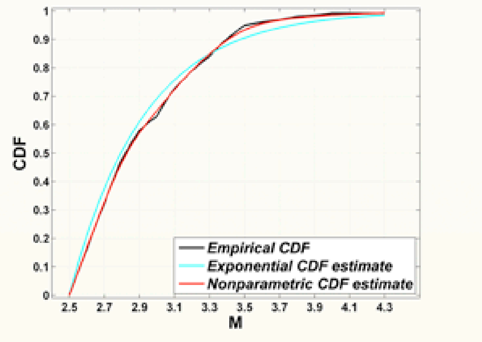


Fig.9. Empirical CDF, the best fitted exponential CDF and the non-parametric, kernel estimate of CDF of magnitude for the series CL1_2.

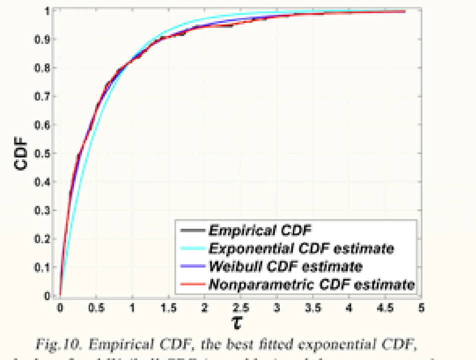


Fig.10. Empirical CDF, the best fitted Weibull CDF (navy blue) and the non-parametric, kernel estimate of CDF (red) of interevent time for the series from cluster CL1_2.

THE GEYSERS

Table 4 contains results of testing the null hypothesis for distribution of *M* and *τ*.

I stage of analysis:
· The results are unequivocal - *M* distribution in none of the analyzed datasets follows the G-R relation born exponential distribution.
· The tests signify the existence of at least two inflection points (one bump) in the probability density function for whole dataset.
· The G-R b-value varies from 0.87 to 1.29 what shows that in case of IIS, the thesis of universality of b-value is definitely incorrect.

II stage of analysis:
The observed *M* distributions are not smoothly non – log linear distributions for the sets **GS09, GS29, GS92**. The tests signify the existence of at least two inflection points (one bump) in the probability density function. The bump in the case of series **GS92** has converted into a fully formed mode. The only series, which does not exhibit such complexity of the *M* distribution (**GS91**), results in p-value 0.125, which is still small compared with the results of the same tests obtained for the Oklahoma dataset.

III stage of analysis:
With one exception, the *M* distribution in the **GIx_up/down** datasets does not follow the G-R relation born exponential distribution. The only counter example belongs to the event group, which occurred after Prati-29 well ceased injecting. This event group is very specific. The activity rate in this group does not appear to depend on the injection rate. For the sets **GI2_up** and **GI3_up** the test signify the existence of at least two inflection points (on bump) in the propability density function.

«««« *M* distribution (τ) distribution »»»»

Stage	$H_{02}^{2}(M)$ Complex distribution: Test p-value	$H_{02}^{1}(M)$ Test p-value	$H_{01}(M)$ Exponential distribution: Test p-value	G-R b-value	β	Largest M	N	Analyzed dataset	N	$H_{01}(τ)$ Exponential distribution: λ [1/day]	Test p-value	$H_{03}(τ)$ Weibull distribution: 1/λ	α	Test p-value
	0.003	0.364	<0.0001	1.15	2.65	3.2	1021	The whole catalog	1120	0.46	<0.0001	0.63	0.61	<0.0001
I stage			0.019	0.87	2.00	2.6	105	G04	104	0.39	0.056	0.31	0.77	0.803
			0.046	1.29	2.98	3.2	102	G07	100	0.74	<0.0001	0.96	0.62	0.057
			0.007	1.25	2.89	2.7	185	G09	184	0.93	<0.0001	0.89	0.70	0.014
			0.016	1.03	2.37	2.6	108	G15	107	0.80	<0.0001	0.90	0.59	0.130
II stage	0.043	0.259	0.000	1.09	2.50	3.1	420	GS09	418	0.33	<0.0001	0.41	0.68	0.005
	0.016	0.462	<0.0001	1.20	2.75	3.2	701	GS29	700	0.60	<0.0001	0.83	0.60	<0.0001
	0.125	0.296	0.004	1.01	2.33	2.7	248	GS91	247	0.29	0.000	0.34	0.75	0.075
	0.054	0.039	0.000	1.22	2.82	3.1	172	GS92	171	0.40	<0.0001	0.54	0.59	0.001
III stage	0.123	0.419	0.004	1.22	2.81	2.7	425	GI1_up	413	0.82	<0.0001	1.08	0.63	0.000
	0.204	0.437	0.000	1.16	2.67	3.2	260	GI1_down	247	0.46	<0.0001	0.64	0.60	0.003
	0.026	0.201	0.001	1.20	2.77	2.7	455	GI2_up	447	0.82	<0.0001	1.15	0.59	0.000
	0.586	0.670	0.021	1.20	2.76	3.2	234	GI2_down	225	0.43	<0.0001	0.54	0.65	0.016
	0.010	0.163	0.001	1.22	2.80	2.7	461	GI3_up	454	0.82	<0.0001	1.13	0.60	0.000
	0.577	0.899	0.008	1.17	2.67	3.2	231	GI3_down	223	0.40	<0.0001	0.53	0.63	0.015
	0.311	0.717	0.006	1.02	2.35	2.7	172	GI4_up	166	0.42	0.004	0.49	0.76	0.910
			0.035	0.98	2.26	2.6	71	GI4_down	65	0.17	0.463	0.19	0.84	0.668
			0.203	1.22	2.82	3.1	86	GI5_up	80	0.48	<0.0001	0.54	0.77	0.307
			0.000	1.22	2.81	3.0	78	GI5_down	72	0.43	0.056	0.73	0.47	0.011

Table 4 Results of tests of hypotheses for magnitude distribution (M) and goodness-of-fit tests of exponential and Weibull distributions for interevent time (τ) of the Geysers data. The test p-values, which implicate the rejection of a null hypothesis at the significance level 0.05, are given in bold red. β - distribution parameter, Largest M - largest magnitude in the sample, λ - mean event rate, 1/λ - scale parameter, α - shape parameter.

I stage of analysis:
· $H_{01}(τ)$ is rejected highly significantly for all but one studied datasets, and the test p-value for the one exceptional is at the limit for rejection (0.056). We can conclude that the *τ* is not governed by an exponential distribution.
· The Weibull distribution models more or less correctly the *τ* distribution in the stationary series - $H_{03}(τ)$. The shape parameter (*α*) is less than one, which indicates a negative ageing property of the earthquake occurrence process - similar as in the case of Oklahoma data.

II and III stage of analysis:
Since the activity rate (λ) is so distinctly dependent on the injection rate, and the latter is varying, it is surprising that the earthquake occurrence process is not fully random (Poissonian) – the *τ* distribution is not exponential - $H_{01}(τ)$. With only two exceptions, in which the sample size is not big, the A-D test rejects the exponentiality hypothesis - **GI4_down** and **GI5_down**. The activity rate variability, induced by the injection rate changeability, seems to be considerable as even the two parameter Weibull distribution model does not fit *τ* data in our datasets - $H_{03}(τ)$. Further studies are needed, to build a model of the injection – seismic activity dependence.

CONCLUSIONS

«««« *M* distribution

· The *M* distribution for the whole Oklahoma dataset as well as for most of the selected space clusters does not follow the exponential distribution. This conclusion is not valid for most of extracted stationary series of seismic events;
· Result suggests that the rejection of the exponential distribution model for the clusters and the whole dataset may be due to time variation of the *M* distribution, which might stabilize in the stationary series of events;
· The tests show that the G-R distribution model is inappropriate for the seismic data from Oklahoma dataset, even though it can properly model some smaller, carefully selected subsets.

(τ) distribution »»»»

· The injection induced process of earthquake occurrence definitely is not a Poisson process - the *τ* do not follow an exponential distribution - the process is not fully random.
· When earthquake occurrences are influenced by a multitude of inducing factors, like in the Oklahoma dataset case not connected with specific injection wells, the *τ* distribution can be modelled by the Weibull distribution supporting a negative ageing property of the process.The negative ageing property means that the probability of occurrence of the next event decreases with the elapsed time since the last event.
· When earthquake occurrences are due to a specific injection activity, like in The Geysers dataset case, the Weibull model for *τ* is not appropriate. The event rate directly depends on the injection rates and responds immediately to the changes of the injection rates. However, these direct correlation and immediate response seem to disappear after the injection rate drops down from an elevated level, which lasted in a longer time period. This conclusion is uncertain yet and the effect will require further studies.

The same conclusion, even stronger supported by the obtained results, is extended over The Geysers data. The *M* distributions insubsets of The Geysers dataset are rough, often multimodal or exhibiting multi bump structure of the probability density. In view of our results and possible negative effects of the use of improper *M* distribution model on hazard estimates, we conclude that in injection induced seismicity:
· The exponential distribution model for *M* is, in general, inappropriate. The earthquake magnitudes do not follow the G-R relation;
· The *M* distribution can be complex, multimodal. In such cases there is no ready-to-use functional model for *M* distribution.
· We recommend to apply non-parametric, kernel estimators of *M* distribution.

Institute of Geophysics PAS
64 Księcia Janusza St.
01-452 Warsaw
www.igf.edu.pl