High injection rates counteract formation of far-reaching fluid migration pathways at The Geysers geothermal field

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Key Points:

- Degree of seismic sources disorder correlates with injection rate and amplitudes of its changes agree with injection rate changes.
- Formation of long pathways for fluid migration requires certain ordering of seismic sources.
- High injection rates increase sources disorder hence decrease chance for seismic fractures to coalesce into long fluid migration pathways.

Abstract

Deep underground water injections induce seismicity. When the seismic fractures coalesce into far-reaching pathways for fluid migration, the migrating fluid may reach pre-existing faults, and by decreasing fault strength, can trigger major seismic events. We assume that the potential for building such pathways depends on closeness of hypocenters, similarity of fracture planes orientations, and closeness of radii taking off from the injection point, on which events locate. We define this potential as the average distance between seismic events in the space of parameters quantifying the above conditions. We show that in the studied case from The Geysers geothermal field, this potential is highly correlated with injection rate. When the overall level of injection rate is high, the higher the injection rate, the more the potential for building far-reaching pathways for fluid migration is reduced.

Plain Language Summary

Geothermal energy production is often based on pumping cold water down to hot rocks and taking back steam. Pressurized underground water injections induce brittle fracturing of rocks, that is seismic events, what enhances the rock permeability and in this way increases the surface on which heat exchange takes place. However, the seismic fractures may also coalesce into undesired pathways enabling the fluids to migrate far and reach pre-existing tectonically preloaded faults. Then the fluids decrease fault strength, and in result the fault can rupture producing a major seismic event. We studied how some properties of the seismicity induced by injections of water in a part of the Geysers, which can lead to the mentioned undesired fracture network development, depend on injection rates. Our studies indicated that the potential for such network development is highly correlated with the injection rate. Moreover, it turned out that in order to avoid this unwanted development of fracture network the injection rates should be kept high. The higher the injection rate is, the more the potential for building far-reaching pathways for fluid migration is reduced. These results, when confirmed on other seismically active geothermal energy production cases can have important implications for strategies of geothermics.

1 Introduction

Deep underground water injections induce seismicity. This seismic fracturing of rocks is desirable as it increases the surface on which heat exchange takes place in Enhanced Geothermal Systems, and enhances the rocks permeability in hydrocarbon extractions based on hydrofracturing. However, the seismic fractures may also coalesce into undesired pathways for fluid migration. These are such pathways that enable the fluids to reach pre-existing faults. In result, by decreasing fault strength, the fluids can trigger ruptures and produce major seismic events. The further the migration pathways extend from the injection point, the more probable are these unwanted effects. It is therefore of paramount importance to recognize under which injection conditions an induced seismic process can produce such pathways (e.g.: Davies et al., 2013; Ellsworth, 2013; Majer et al., 2012; Zhang Dongxiao & Yang Tingyun, 2015).

Numerous studies indicate that the geometry of fractures and the structure of fracture networks are the main factors controlling fluid flow and the fluid transport characteristics of rocks (e.g.: Hope et al., 2015; Lee et al., 1990; Long & Billaus, 1987; Schwartz et al., 1983; Snow, 1965). The development of the fracturing process has been investigated in a number of laboratory experiments (e.g.: Ko & Kemeny, 2011; Lockner et al., 1992; Stanchits et al., 2006).

Based on these experiments, many models have been developed to simulate the geometry of fractures and the topology of fracture networks (e.g.: Hope et al., 2015; Lee et al., 1990; Long & Billaus, 1987). However, although seismic field data provide direct insight into the development of fracture networks at the crustal scale, there are few studies focused on this topic (e.g.: Chorozoglou et al., 2018; Orlecka-Sikora et al., 2019; Sausse et al., 2010).

Here we study seismic and injection data from a part of the Geysers geothermal field to determine a relation between the injection conditions and the potential of injection-induced seismicity to build far-reaching pathways for fluid migration. We formulate three conditions determining this potential: 1. Closeness of hypocenters; the closer the sources are to each other, the higher the likelihood that they will connect. 2. Similarity of fracture plane orientation; the system of linked fractures is more extended in length when the rupture planes of the fractures are oriented more parallel. 3. Closeness of radii, which begin at the open hole section of the injection well and on which events occur; the system of linked fractures reaches farther from the open hole when the seismic sources are located on radii close to each other.

Consequently, seismic events are represented by eight parameters: three hypocentral coordinates, three independent angles determining orientations of the T and P axes of the double-couple (DC) focal mechanisms, and two angular coordinates of hypocenters in the spherical system beginning at the open hole of injection well. To achieve the same scaling of these parameters, we transform them to equivalent dimensions (Lasocki, 2014; Supporting Information Text S1). The potential for building the far-reaching fluid migration pathways is quantified by the average distance between the events in the 8-dimensional space of the aforementioned parameters. When this average distance, which we refer to as the degree of disordering of sources, *ZZ*, decreases, the potential for building the pathways increases.

We show that the degree of disordering of sources, *ZZ*, is highly significantly correlated with the injection rate. *ZZ* took the highest values when the injection rates were the highest, which indicates counterintuitively that high injection rates counteracted the formation of far-reaching fluid migration pathways.

2 Data and Methods

The Geysers geothermal field is located in northern California, US. Geothermal operations, which began there in the 1960s, and which presently use EGS technology, have induced hundreds of thousands of seismic events. We studied injection and seismic data from an isolated part of the field of 2 km × 2 km dimension in the NW part of The Geysers, between 10 December 2007 and 23 August 2014. The basis for the seismic dataset was an improved catalog that contained 1252 events (Kwiatek et al., 2015; Martínez-Garzón et al., 2014; 2016). This unique catalog provided all the event parameters, necessary for the calculation of the degree of disordering of sources, *ZZ*: hypocenter locations with an accuracy of 50 m, and focal mechanisms with an accuracy of 20°/5°/10° for strike/dip/rake. The focal mechanisms were recalculated using HASH software assuming a double-couple shear source (Hardebeck & Shearer, 2002; Kwiatek et al., 2015; Martínez-Garzón et al., 2016) and were used to recover the trend and plunge angles of the T and P axes. The moment magnitude was used and the completeness level was Mc=1.4 (Kwiatek et al., 2015).

In the study period, the injections in the study area were carried out into two wells: Prati9 and Prati29. There were three phases of the injection activity:

- Phase F1 from 10 December 2007 to 10 April 2010, in which only Prati9 was operational,
- Phase F2 from 11 April 2010 to 21 June 2013 with simultaneous injections into both wells,
- Phase F3 from 11 June 2013 to the end of the study period (23 August 2014), in which again only Prati9 was operational.

The injection data consisted of the daily injection volumes into Prati9 and Prati29.

The 1252 events formed two distinct spatial clusters: cluster A located around the open hole of Prati9 well and cluster B comprising events located closer to the open hole of Prati29 well (see: Supporting Information Figure S1). We studied more numerous cluster A, consisting of 1121 events. We expected that this cluster, being spatially related to the open hole of Prati9 well, was also physically related primarily to the injection activity in Prati9.

The parameter used here to quantify the potential for building the far-reaching fluid migration pathways, called as the degree of disordering of sources, *ZZ*, was the average distance between the seismic events in the 8-dimensional parameter space $\{x_1, x_2, x_3, plu\_X_1, plu\_X_2, tre\_X_1, \Theta, \varphi\}$. $x_{1,2,3}$ were hypocenter coordinates. plu_X_1 and tre_X_1 were plunge and trend angles of the T axis. plu_X_2 was a plunge angle of the P axis. Θ, φ were the polar and azimuthal angles of hypocenter in the spherical system of coordinates beginning at the open hole of Prati9 well. Θ=0 for the vertical direction and φ=0 for the N direction. These parameters were not comparable. For this reason, we first transformed them to equivalent dimensions (ED). The transformation to ED is a technique based on a probabilistic equivalence of the parameters that scale differently (Lasocki, 2014 and Supporting Information Text S1). All transformed parameters are uniformly distributed in [0,1] and the distance between any two objects is the Euclidean metric. Further on the symbols $x_1, x_2, x_3, tre\_X_1, tre\_X_2, plu\_X_1, plu\_X_2, \Theta, \varphi$ denote the equivalent dimensions of the original source parameters.

The closeness of hypocenters was unequivocally parameterized by the absolute differences between hypocenter coordinates, $\Delta x_k(i,j) = |x_k(i) - x_k(j)|, k = 1,2,3$.

The trend angle and the polar angle take values in [0^o, 180^o], which is [0, 1] in ED, and the azimuthal angle takes values in [0^o, 360^o], which is also [0,1] in ED. The shortest distances between these angles in ED were therefore:

$$\Delta tre\_X_1(i,j) = 2\begin{cases} |tre\_X_1(i) - tre\_X_1(j)| & if \;\; |tre\_X_1(i) - tre\_X_1(j)| \le 0.5 \\ 1 - |tre\_X_1(i) - tre\_X_1(j)| & if \;\; |tre\_X_1(i) - tre\_X_1(j)| > 0.5 \end{cases}, \quad (1)$$

$$\Delta\theta(i,j) = 2\begin{cases} |\theta_i - \theta_j| & if \;\; |\theta_i - \theta_j| \le 0.5 \\ 1 - |\theta_i - \theta_j| & if \;\; |\theta_i - \theta_j| > 0.5 \end{cases}, \quad (2)$$

$$\Delta\varphi(i,j) = 4\begin{cases} |\varphi(i) - \varphi(j)| & if \;\; |\varphi(i) - \varphi(j)| \le 0.25 \\ \big|0.5 - |\varphi(i) - \varphi(j)|\big| & if \;\; 0.25 < |\varphi(i) - \varphi(j)| \le 0.75 \\ 1 - |\varphi(i) - \varphi(j)| & if \;\; |\varphi(i) - \varphi(j)| > 0.75 \end{cases}. \quad (3)$$

The multipliers in front of the opening braces in equations (1-3) were inserted so that the differences in all parameters scaled in [0, 1].

The plunge angle takes values in [0^o, 90^o]; hence, $\Delta plu\_X_k(i,j)$ was always $|plu\_X_k(i) - plu\_X_k(j)|$, k=1,2.

For a collection of *n* seismic sources the degree of disordering of sources, *ZZ* reads:

$$ZZ = \left\{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} ZZ(i,j)\right\} / \frac{n(n-1)}{2} \quad (4)$$

where

$$ZZ(i,j) = \sqrt{\left[\sum_{k=1}^{3} \Delta x_k(i,j)^2\right] + \left[\Delta tre\_X_1(i,j)^2 + \sum_{k=1}^{2} \Delta plu\_X_k(i,j)^2\right] + \left[\Delta\theta(i,j)^2 + \Delta\varphi(i,j)^2\right]} = \sqrt{\Delta_r(i,j)^2 + \Delta_M(i,j)^2 + \Delta_\phi(i,j)^2} \quad (4a)$$

$\Delta_r(i,j)$ is the distance between hypocenters of events *i* and *j*;

$\Delta_M(i,j)$ is the distance between focal mechanisms of these two events;

$\Delta_\phi(i,j)$ is the distance between the directions of radii from the Prati9 open hole, those on which the hypocenters of these two events locate.

We carried out our analyses separately in the three injections phases. Out of 1121 studied events, 248 events occurred in the injection phase F1, 702 events – in the phase F2 and 171 events – in the phase F3. For every injection phase we calculated *ZZ* for 50-event window sliding by 10 events. The number of events per phase was not high enough to use non-overlapping windows. For sliding windows we obtained 21 *ZZ* values for F1, 66 *ZZ* values for F2 and 13 *ZZ* values for F3.

Next, we calculated the average injection rates, *IN*, during time windows covering the periods of the 50-event sliding windows, respectively. The calculations were performed for the injection rate periods exactly matching the periods of respective 50-event windows and for the injection rate periods from 1 to 21 days preceding the periods of event windows. The latter part of this analysis was meant to study delayed reactions of seismicity.

Finally, we studied the correlation between *ZZ* – values and *IN* – values. It comes from equation (4a) that *ZZ* is composed of three components representing our three conditions determining the potential of injection-induced seismicity for building far-reaching pathways for fluid migration. In order to recognize contributions of these components to the correlations between *ZZ* and *IN* we studied also the correlations between $\Delta_r, \Delta_M, \Delta_\phi$ – values and *IN* – values, respectively.

All correlation analyses were preceded by the Jarque-Bera test applied to check normality of the distributions of the used variables. If the normality hypothesis was not rejected we used the Person's correlation; in rare otherwise cases we used the Spearman rank correlation.

We also tested differences between the values of location parameters by phase of *IN*, *ZZ*, seismic activity rate and magnitude, respectively. When the normality hypothesis for a parameter was not rejected, we used the Student's t-test for means, otherwise we applied the Mann-Whitney U-test for medians. All statistical inferences were performed under the significance level α=0.05.

3 Results and Discussion

Some descriptive statistics by phase of *IN*, *ZZ*, seismic activity rate and magnitude of events are presented in Table 1 together with comparisons of their location parameters (means or medians) among phases. The medians of injection rates into Prati9 well were decreasing statistically significantly with injection phase.

Table 1. Descriptive statistics and comparisons of the average injection rate, IN, the degree of disordering of seismic sources, ZZ, the activity rate, and magnitude of events in the three injection phases. The magnitude was transformed to the equivalent dimension. The statistics of these parameters concern their respective values from sliding event windows. The column "Comparisons" contains *p*-values of the tests of differences between means or medians of these parameters. The significant differences are in bold.

	Injection phase									**Comparisons of location parameters, *p*-value**		
	F1			**F2**			**F3**			**F1 vs. F2**	**F2 vs. F3**	**F1 vs. F3**
	Mean	**Med.**	**Std. dev.**	**Mean**	**Med.**	**Std. dev.**	**Mean**	**Med.**	**Std. dev.**			
Prati9 *IN* [100m^3/day]	43.76	45.18	13.09	36.18	35.69	11.51	29.10	30.95	8.18	**0.024**	**0.014**	**3E-4**
Summed Prati9 and Prati29 *IN* [100m^3/day]	43.76	45.18	13.09	72.82	73.43	22.54	29.10	30.95	8.18	------------------------		
ZZ	1.402	1.403	0.012	1.439	1.438	0.021	1.401	1.396	0.015	**5E-14**	**2E-7**	0.91
Activity rate [event/day]	0.35	0.34	0.13	0.70	0.69	0.23	0.48	0.44	0.11	**7E-12**	**6E-6**	**7E-3**
Magnitude	0.55	0.57	0.06	0.49	0.49	0.04	0.45	0.47	0.06	**3E-4**	0.055	**2E-4**

Figure 1 compares the time-variations in the degree of disordering of sources, *ZZ*, with the variations of the average injection rate, *IN*. In phase F2 this comparison concerns the injection rate into Prati9 well, *IN*(9), and the total injection rate into both wells, *IN*(both). It is seen in the figure that in the first two injection phases, F1, F2, *ZZ* correlated positively with *IN*. Also the amplitudes of the *ZZ*-changes agreed well with the amplitudes of the average injection rate changes. In phase F2, this agreement related to the summed injection into both wells (blue curve) rather than Prati9 well alone (black curve), even though the analyzed seismic events were geometrically linked to Prati9 (Supporting Information Figure S1).

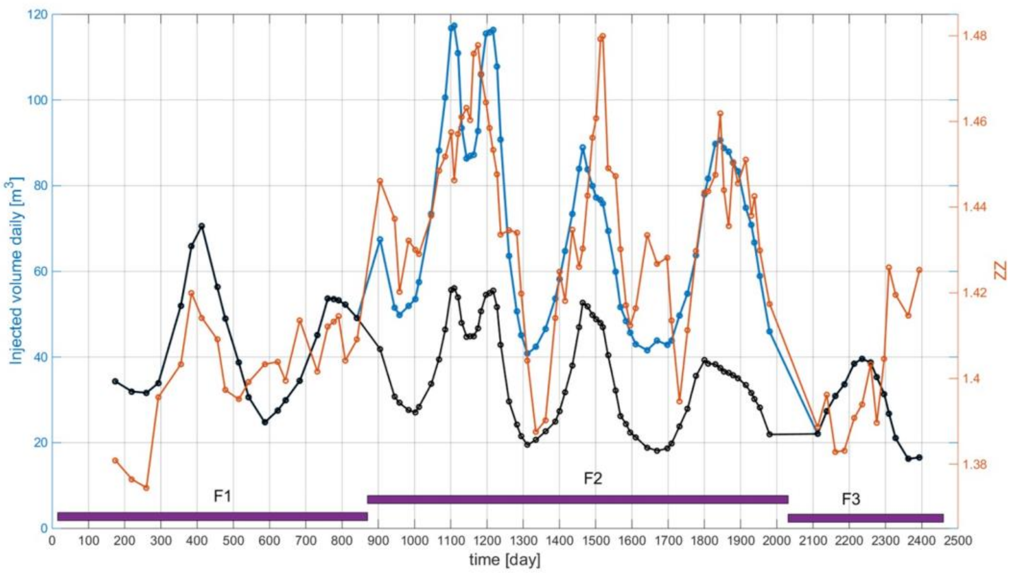

Figure 1. Comparison of the time-variation of the degree of disordering of sources, *ZZ*, with the time-changes of average injection rate. Black – the injection rate into Prati9 well, blue – the total injection rate into Prat9 and Prati29 wells, brown – *ZZ*. The horizontal bars mark the durations of the three injection phases. The injection rate values are the daily injection volumes averaged over the times covered by the event windows, respectively.

Table 2 presents the results of analysis of correlations between the injection rate, *IN*, and the degree of disordering of sources, *ZZ*. These results confirm the correlations evidenced in Figure 1. In F1 and F2 the correlation between *IN* and *ZZ* was significant, positive. In F2 this correlation was highly significant, irrespective of whether the *IN* referred to injections into Prati9 or to the summed injections into Prati9 and Prati29 wells.

Table 2. Results of the correlation analysis between the average injection rate, *IN*, and the degree of disordering of seismic sources, *ZZ*, and its components, $\Delta_r, \Delta_M, \Delta_\phi$. For the phase F2 row 'a' provides the correlation between *ZZ* and *IN* into Prati9 well, and row 'b' provides the correlation between *ZZ* and total *IN* into Prati9 and Prati29 wells. The significant correlations are in bold. The results based on Spearman rank correlation are in italics.

Injection phase	*ZZ*		Δ_r		Δ_M		Δ_ϕ	
	Corr. coef.	*p*-value	Corr. coef.	*p*-value	Corr. coef.	*p*-value	Corr. coef.	*p*-value
F1	**0.62**	**0.002**	**0.69**	**$5\cdot10^{-4}$**	0.20	0.37	-0.28	0.22
F2 – a	**0.76**	**$2\cdot10^{-13}$**	**0.69**	**$2\cdot10^{-10}$**	**0.41**	**$7\cdot10^{-4}$**	***0.49***	***$3\cdot10^{-5}$***
F2 – b	**0.72**	**$7\cdot10^{-12}$**	**0.65**	**$1\cdot10^{-9}$**	**0.45**	**$1\cdot10^{-4}$**	***0.47***	***$8\cdot10^{-5}$***
F3	**-0.60**	**0.029**	-0.20	0.51	-0.32	0.28	-0.19	0.52

The results of correlation analysis for delayed *ZZ* with respect to *IN* are presented in Supporting Information Tables S1-S4. In F1 the correlation coefficient slowly decreases with increasing lag. The correlation coefficient in F2 slightly increased when *ZZ* was delayed with respect to *IN*, however the difference between the correlation coefficient for zero lag and for 13 days lag was only 0.022 and was surely insignificant.

The previous studies of the same data have indicated a positive correlation between seismicity rates and injection rates (Leptokaropoulos et al., 2018). Hence different time periods corresponded here to the 50-events windows; the time periods at higher injection rates were shorter. We checked whether the positive *ZZ* vs. *IN* correlations were not due to these differences between time periods. For this purpose we divided the F2 phase into non-overlapping windows of constant, 68 days duration. The correlation between *IN* and *ZZ* both calculated for these windows of constant time period, was also positive (0.87) and significant (p = 0.0097).

In F1 only Δ_r out of three components of *ZZ* (see: Data and Methods, Equation 4a) significantly and positively correlated with *IN*. The correlation was the highest for zero lag (Supporting Information Table S1). Hence, in this injection phase the positive *ZZ* - *IN* correlation resulted from that that higher injection rates were increasing distances between the sources. However, this effect was not caused by moving away of sources from the well opening of Prati9. In neither phase the correlation coefficient between *IN* and the average distance of hypocenters from the open hole was significant.

In F2 all three distances, $\Delta_r, \Delta_M, \Delta_\phi$, were highly positively correlated with *IN* thus they all significantly contributed to the correlation *ZZ* – *IN*. Higher injection rates led to an increase of the distances between hypocenters, to a greater variety of P and T axes directions and to a greater angular dispersion of the hypocentres in relation to the open hole of Prati9 well. Nothing more interesting was obtained from the correlations when *ZZ* was delayed with respect to *IN* (Supporting Information Tables S2-S3).

A way in which increased injection rates may increase the degree of disordering of sources (*ZZ*) is shown schematically in Figure 2. An increase of pore pressure resulting from the increased injection rate broadens the range of possible orientations and locations for new shear fractures.

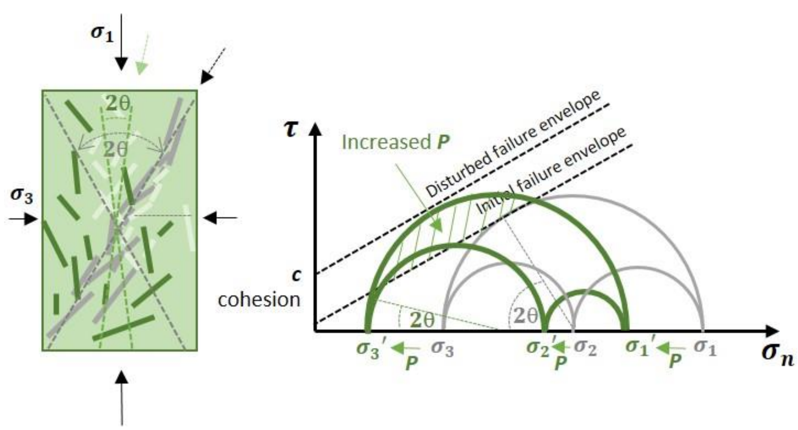

Figure 1. Schematic presentation of influence of pore pressure (P) changes on the failure plane orientations. The linear failure criterion imposes that shear fractures make with σ_1 a well-defined angle of (±) 45°−φ/2, where φ is the angle of internal friction, and θ=ϕ/2+45 (gray circle in Coulomb-Mohr diagram and gray fractures on the rock block on the left). An increase of P reduces the effective normal stress, σ_n', where $\sigma_n' = \sigma_n - P$ and broadens the range of possible

orientations for new shear fractures (all directions going through green hatched area in the Coulomb-Mohr diagram and green fractures on the rock block) (after Warren-Smith et al., 2019).

The previous studies of the fracture network development, carried out on the same data, have shown that the connectivity of fractures induced by fluid injection is lower for higher injection rates and *vice versa* (Orlecka-Sikora et al., 2019). Thus the connectivity was responding to the injection rate changes in the same way as *ZZ*. This allows for inferring that *ZZ* indeed represents the potential of fluid migration. In the cited work the connectivity was estimated by the connectivity coefficient, *C*, defined by the ratio of the observed number of intersections of fractures in a fracture network to the number of all possible intersections in this network. These all possible intersections were evaluated as $0.5f(f-1)$, where *f* was the number of fractures building the fracture network (21, 22)

In the F3 phase, in which the overall level of the injection rate, *IN*, was the lowest among injection phases, the correlation between *IN*, and the degree of disordering of sources, *ZZ*, was significant, negative. This correlation was achieved only jointly by the three components of *ZZ*: $\Delta_r, \Delta_M, \Delta_\phi$ because neither of the them significantly correlated with *IN* (Table 2). The negative correlation coefficient in F3 increased when *ZZ* was delayed with respect to *IN*, and for 4 and more days lag it became statistically not significant (Supporting Information Table S4). The change of sign of the *IN* – *ZZ* correlation in F3 may be explained by the role of injection rate changes on the weakening/strengthening of rock. According to rock sample studies of Fjaer and Ruisten (2002) in rock weakening conditions there are many equivalent orientations of the failure plane, and the fracture orientation is determined by local weaknesses of the rock. In conditions of rock strengthening only two orientations for the potential failure plane fulfil the Coulomb failure criterion. Thence rock weakening conditions result in poorly ordered seismic fractures, and in rock strengthening conditions the fractures are better ordered. Orlecka-Sikora and Cielesta (2019) found two mutually reversed reactions of the stress field to injection rate changes in The Geysers, with the reversal point at some $50\text{-}70{\cdot}10^2$ m^3/day. At injection rates above this interval, increasing the injection rate enhanced rock weakening, and a decrease in the injection rate led to rock strengthening. Below this interval, the effect of injection rate variation was the opposite.

The injection rates in F1 and F2 were mostly above the aforementioned reversal point. To the contrary, the injection rates in F3 were well below this point. In the first two phases, weakening of the rock with increasing injection rate could favor the formation of randomly oriented fractures, which was expressed by the increase in the degree of disordering, *ZZ*. In F3 increasing the injection rate could lead to rock strengthening, which promoted the formation of fractures oriented in the optimal direction. As a consequence, the fractures were better ordered, which reduced *ZZ*.

The second well, Prati29, was operational only in F2 phase. In this phase the amplitudes of *ZZ* changes agreed with the amplitudes of changes of the summarized injections into Prati9 and Prati29. Furthermore, the mean level of *ZZ* and the mean seismic activity were the highest in this phase and significantly higher than in phases F1 and F3. In F2 only the level of total injection into Prati9 and Prati29 was the highest, and the mean level of injection rate into the Prati9 well was significantly smaller than in phase F1 (see: Table 1). All these indicate the important role of the injections into Prati29 for the generation of seismic events within the studied cluster A in spite of the considerable distance between the open hole section of Prati29 well and the events from cluster A.

The seismic events generated at higher injection rates, i.e. the ones more disordered (*ZZ* was higher), did not have greater magnitudes. On the contrary, in the F1 phase the mean magnitude in windows correlated negatively with *ZZ* (corr. coef. -0.61, $p = 0.003$. In the F2 phase no magnitude – *ZZ* correlation was observed.

4 Conclusions

Studying the actual field data we found exceptionally high and immediate correlation between the injection rate and the seismicity parameter - the degree of disordering of sources, *ZZ*. Also the amplitudes of ZZ-changes agreed very well with the amplitudes of the average injection rate changes. *ZZ* is defined solely on parameters of seismic sources. It describes how much seismic fractures are dispersed in terms of distances between their hypocenters, mutual orientations of their fracture planes, and angular dispersion of their hypocenters.

We interpret *ZZ* as a measure of the potential of seismic fractures for building far-reaching pathways for fluid migration. The logic of the three conditions on which *ZZ* is based, supports this interpretation though these conditions are certainly not adequate for all possibilities of fracture network development (e.g. not for a percolating fluid pathway).

In the studied case from The Geysers geothermal field, the optimal conditions to avoid such ordering of seismic fractures that enable linking them into longer pathways, extending farther from the injection point were met for high injection rates. The higher the injection rate was, the more disordered the seismic fractures were generated, i.e., the chances to build longer pathways for undesired fluid migration was decreased. High injection rates caused an increase in seismic activity, nevertheless the median level of seismic event magnitudes remained unaffected.

The above conclusion, if confirmed in other cases of injection induced seismicity, would open new perspectives on managing seismic hazards and optimizing technological production. Martinez-Garzon, et al. (2018) conclude that the used here dataset from the NW region of The Geysers well represents the broader seismic processes at The Geysers field. Thus our results may be also valid for all seismic processes at The Geysers. However, for further generalizations studies of other injection-induced seismicity cases are required.

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