

Independence of Spatial and Temporal Static Stress-Drop Variability at The Geysers Geothermal Field

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Abstract

The variability of static stress drop of earthquakes has been described in several studies concerning injection-induced seismicity. In this work, we refer to temporal and spatial variability of static stress drop identified originally by Staszek *et al.* (2017) and Staszek *et al.* (2021) in the cluster of seismicity induced by cyclic fluid injection into Prati-9 and Prati-29 wells at The Geysers geothermal field (California, United States). Stress drops of events within this cluster fell in the range 0.7–58.3 MPa with a median value of 4.7 MPa. The temporal stress-drop variability described by Staszek *et al.* (2017) was identified among three time intervals and was found to be inversely related to the injection rate. The spatial variability of stress drop described by Staszek *et al.* (2021) resulted from the differences in stress drop between the events delineating identified fault and fractures. Here, we assess the significance of stress-drop variations in time in different groups of events and show that temporal stress-drop variability remains statistically significant even after excluding the fault-related events exhibiting significantly lower stress-drop values. Therefore, in this case the spatial and temporal variations in static stress drop are independent. Moreover, we confirm that there is an inverse relation between static stress drop and injection rate and conclude that pore pressure changes do influence the static stress drop of earthquakes in the area, regardless of the spatial heterogeneity of the reservoir. We deduce that static stress drop is a parameter influenced by both structure of the reservoir, that is, fracture and fault network, and the dominant physical process responsible for the generation of earthquakes. Therefore, we suggest that static stress drop should be interpreted after considering both spatial and temporal variability contributions, if possible, in the frame of specific structures.

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Introduction

Static stress drop ($\Delta\sigma$) is a parameter of seismic source that reflects the change of shear stress on the fault due to an earthquake. Whereas absolute stresses cannot be obtained from radiated waves in the proximity of the faulting area, we can calculate the value of stress released during an earthquake, that is, static stress drop. This parameter can be used to get some overview of earthquake source and its dynamics. Moreover, static stress drop is a parameter influencing the ground motions generated during an earthquake: for two events with the same magnitude, the ground velocities are significantly higher for the higher stress-drop event (Abercrombie, 2021). Therefore, accurate calculation and assessment of this parameter is also of interest for seismic hazard and risk assessment studies.

Spatial and temporal variability of static stress drop of events induced by fluid injection was recognized in many recent studies and usually attributed to the changes of frictional

strength of discontinuities. Under fluid injection conditions, an observable decrease in the frictional strength is related to the increase in pore pressure and consequent decrease of the effective normal stress acting on the discontinuity (von Terzaghi, 1936). The explanation of spatial stress-drop variability with pore pressure change was proposed, for example, by Goertz-Allmann *et al.* (2011) and Kwiatek *et al.* (2014), who observed an increase of $\Delta\sigma$ with the distance from the injection wells. They analyzed data sets from Basel geothermal site (Switzerland) and Berlin geothermal site (El Salvador).

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A similar observation was made in the Salton trough (Southern California) by [Chen and Shearer \(2011\)](#), who described lower $\Delta\sigma$ values within the geothermal fields and suggested $\Delta\sigma$ dependence on the distance from the injection wells. Temporal variations of static stress drop during the injection process were described by [Lengliné et al. \(2014\)](#) and [Cauchie et al. \(2020\)](#) at Soultz-sous-Forêts geothermal site (France), and by [Staszek et al. \(2017\)](#) at The Geysers geothermal field. From the perspective of natural earthquakes, [Yoshida et al. \(2017\)](#) described significant temporal variations of $\Delta\sigma$ positively correlated with the variations of frictional strength of faults also attributing them to pore pressure changes. This observation was made after analyzing a seismic swarm, which occurred due to migration of fluids in Yamagata–Fukushima border following the 2011 Tohoku–Oki earthquake.

The differences in static stress drop of earthquakes were also described in the literature from the perspective of structural heterogeneity of rock. For example, [Kwiatek et al. \(2011\)](#) observed that $\Delta\sigma$ of events were lower in the highly fractured rocks at the exploitation level of Mponeng gold mine (South Africa) than in the undamaged rock in this area. Recently, [Yu et al. \(2020\)](#) suggested that lower $\Delta\sigma$ values, which they observed for earthquakes occurring near the well bore at hydraulic fracturing site in British Columbia (Canada), may be related to the higher density of fractures there compared to the intact rock away from the well. Such reasoning is supported by the results of numerical modeling performed by [Zhang and Sanderson \(2001\)](#), who examined the effect of stress on the stability of fractured rock mass. The authors observed a steady decrease in equivalent friction coefficient with increasing fracture density. This observation is also consistent with the theory of rock strength, which says that the rock is much more resistant to brittle fracture, described by the coefficient of internal friction, than to frictional slip described by the coefficient of static friction ([Engelder, 1993](#)). Therefore, it is reasonable to expect that $\Delta\sigma$ calculated from the events generated by the brittle fracture of intact rock will be higher than $\Delta\sigma$ calculated from the events originating from the frictional slip on pre-existing discontinuities ([Griffith et al., 2009](#)). Considering the problem in the scale of one fault plane, [Zielke et al. \(2017\)](#) investigated the influence of fault roughness and strength heterogeneity on stress-drop values. Using numerical simulations, the authors showed that smooth (more mature) faults are weaker than rough (immature) faults and they generate earthquakes with smaller stress drops.

Another aspect of stress-drop variability is the physical process responsible for the earthquake generation. As aforementioned, the most often considered process responsible for observed stress-drop variability is pore pressure increase and the reduction of effective normal stress on the fault. However, another aspect of the influence of pore pressure on the strength of rock was studied by [Acosta et al. \(2018\)](#), who performed a series of laboratory stick-slip experiments on Westerly Granite saw-cut samples and observed that stress drops of

detected stick-slip events are lowering with increasing fluid pressure. The observation was explained by the lower static friction coefficient in the presence of fluids, which results from a reduction of adhesion along the fault surface in the presence of water. Moreover, several authors suggested that aseismic slip on the fault may influence stress drops of generated events. [Huang et al. \(2019\)](#) analyzed microseismic sources registered during injection experiment in France and suggested that faults with low stress may be initially dominated by aseismic slip and induce earthquakes with relatively low stress drops. On the contrary, faults that are critically stressed may primarily slip seismically and be the source of events with relatively high stress drops. The process of slow slip leading to the reduction of fault strength was suggested to explain relatively low values of $\Delta\sigma$ of foreshocks recorded before the 1992 Landers and 1999 Hector Mine earthquakes in the area of the San Andreas fault ([Chen and Shearer, 2013](#)). Similarly, [Chen et al. \(2024\)](#) found that $\Delta\sigma$ of events that occur in the segment of the Main Marmara fault where the fault slip is released partly aseismically are significantly lower than $\Delta\sigma$ of events occurring in other parts of the fault. They also suggested that aseismic slip could contribute to lowering the fault strength and, therefore, stress drops of events. Finally, the dependence of source parameters on the physical process was suggested by [Cauchie et al. \(2020\)](#). They demonstrated that the population of repeating events, related to the process of aseismic slip on pre-existing fault, is characterized by smaller source radii than the population of repeaters originating from the initiation of new fractures.

As shown in the previous works, static stress drops of seismic events in the area of Prati-9 and Prati-29 injection wells, at the northwestern part of The Geysers geothermal field, exhibit twofold variability: (1) temporal variability, with distinguished three time intervals (TIs) exhibiting significantly different median values of stress drop and its distributions ([Staszek et al., 2017](#)), and (2) spatial variability, with stress drop depending on the type of structure and the number of activation episodes ([Staszek et al., 2021](#)). The statistical significance of temporal variability of stress drop in this area was assessed by applying the nonparametric Wilcoxon rank sum test and two-sample Kolmogorov–Smirnov test to the pairs of moving constant-event windows with the size of 20–70 events. On the basis of obtained results, three TIs with significantly different medians and distributions of $\log(\Delta\sigma)$ were distinguished: (TI1) 1 February 2010 to 13 September 2010 with median $\Delta\sigma = 5.7$ MPa, (TI2) 23 September 2010 to 21 August 2011 with median $\Delta\sigma = 3.8$ MPa, (TI3) 28 August 2011 to 7 August 2014 with median $\Delta\sigma = 5.3$ MPa. This division was confirmed to be correct after taking into account stress-drop estimation uncertainties and varying sizes of analyzed event windows. Most importantly, temporal variability of stress drop in this area was recognized to be inversely related to the injection rate and interpreted as a straightforward result of pore pressure variations ([Staszek et al., 2017](#)).

In their later work, [Staszek et al. \(2021\)](#) performed double-difference relocation of very similar events (multiplets) to resolve the structure of the reservoir. Similar events were identified using cross correlation of three-component signals. The clustering of events was performed using the unweighted pair group method with arithmetic mean ([Romesburg, 2004](#); [Hayward and Bostock, 2017](#)), with summed three-component cross-correlation coefficient limit equal 2.7 (an average of 0.9 per component). All events belonging to any group of similar events, with minimum size of three events, were classified as “multiple events” (ME). Remaining events were classified as “single events” (SE). Subsequently, all ME were relocated with double-difference relative relocation method developed by [Waldhauser and Ellsworth \(2000\)](#), with the use of highly precise travel-time differences determined from signal cross correlation. As a result of relocation procedure, an image of four underground structures was obtained: (1) three structures (A–C) classified as fractures, due to their linear orientation, and delineated by 22, 7, and 28 ME, respectively, and (2) one structure (D) classified as a fault plane, due to its planar orientation, and delineated by 95 ME (Fig. 1c–d). The structures were delineated via visual inspection of the spatial distribution of relocated ME. After analyzing stress drops of the events, the authors observed that stress drops of ME are significantly lower than stress drops of SE with median values of $\Delta\sigma$ equal to 3.9 and 4.9 MPa, respectively. Specifically, the most numerous group of ME, which delineate the recognized fault D, exhibited lower stress-drop values (with median value of 3.4 MPa) than all the remaining events, that is, SE and ME delineating the fractures A–C (median stress-drop value equal to 4.8 MPa). Described structure-oriented spatial stress-drop variability was interpreted as a result of the structural heterogeneity of the reservoir and suspected development of damage zone along the identified fault ([Staszek et al., 2021](#)).

Having in mind the observations described earlier, the logical question that needs to be answered is whether the temporal stress-drop variability, originally described by [Staszek et al. \(2017\)](#), is actually not an artifact of its spatial variability, identified later by [Staszek et al. \(2021\)](#). This question becomes particularly important knowing the fact that seismic activity within the identified fault D, which is delineated by ME with significantly lower stress-drop values, started in the second TI (fig. 3d in [Staszek et al., 2021](#)), which is also characterized by significantly lower values of stress drop ([Staszek et al., 2017](#); Fig. 2c). Therefore, the main contribution of this work lies in examining whether spatial and temporal differences in static stress drop, identified in the previous studies, are independent of each other and still significant after their separation. Assuming the physical interpretation presented earlier, answering this question would reveal whether, in analyzed case study, static stress drop of earthquakes is influenced by both pore pressure variations and the reservoir heterogeneity, and whether their impacts can be assessed quantitatively. For this

purpose, we assess the significance of stress-drop variations in time in several different groups of events. Performed analysis is complemented by the examination of the influence of stress-drop estimation uncertainties on the obtained results.

Data

In the analysis, we used static stress drops of 321 seismic events that occurred in the area of Prati-9 and Prati-29 injection wells in the northwestern part of The Geysers geothermal field between 1 February 2010 and 7 August 2014 (Fig. 1c,d). The events were recorded by the seismic network consisting of 31 three-component, 4.5 Hz geophones deployed on the surface and sampling with the frequency of 500 Hz (Fig. 1a). The analyzed cluster of seismicity is spatially separated from other seismic events and injection wells of The Geysers geothermal field (Fig. 1a,b), which makes it a valuable case study for understanding how injection operations influence induced seismicity (e.g., [Martínez-Garzón et al., 2014](#); [Kwiatek et al., 2015, 2016](#); [Martínez-Garzón, Kwiatek, et al., 2016](#); [Martínez-Garzón, Vavrycuk, et al., 2016](#); [Martínez-Garzón et al., 2017, 2018](#); [García-Aristizabal, 2018](#); [Leptokarpoulos et al., 2018](#); [Leptokarpoulos and Staszek, 2019](#); [Orlecka-Sikora et al., 2019](#); [Lasocki and Orlecka-Sikora, 2020](#); [Leptokarpoulos, 2020](#); [Leptokarpoulos and Lasocki, 2020](#); [Orlecka-Sikora and Cielesta, 2020](#); [Shirzad, 2024](#)).

Seismic events chosen for the analysis come from the high-quality catalog elaborated by [Kwiatek et al. \(2015\)](#) and available via EPISODES Platform (see [Data and Resources](#); [IS EPOS, 2017](#); [Leptokarpoulos et al., 2019](#); [Orlecka-Sikora et al., 2020](#)). The stress drops were calculated using mesh spectral ratio technique by [Kwiatek et al. \(2015\)](#), with uncertainties estimated by [Staszek et al. \(2017\)](#). The technique suppresses the influence of poorly known propagation, site, and sensor effects on the source parameters of events forming a cluster (see [Kwiatek et al., 2011, 2014, 2015](#); [Harrington et al., 2015](#) for applications). In the first step of calculations, the seismic events were divided into six families basing on their similarity level. The similarity between the two events was quantified by their interevent distance and 3D rotation angle between P, T, and B axes ([Kagan, 1991, 2007](#)). In the second step, within each family the spectral ratios between observed *P*-wave velocity spectra were calculated for any two events with interevent distances < 200 m. Observed spectral ratios were compared to the synthetic ones forming a nonlinear inverse problem with *N* corner frequencies (f_c) and *N* seismic moments (M_0), in which *N* is a number of events in the family. Markov chain Monte Carlo Metropolis–Hastings algorithm ([Metropolis et al., 1953](#); [Hastings, 1970](#); [Mosegaard and Tarantola, 1995](#)) was used to sample the a posteriori distribution of source parameters and obtain 2D marginal probability density distribution in M_0 – f_c space for each event. These distributions were used to calculate mean static stress-drop values, following the formula of [Eshelby \(1957\)](#) and assuming the circular source model proposed by [Madariaga \(1976\)](#) with scaling constant $k=2.01$, corresponding to constant rupture velocity of

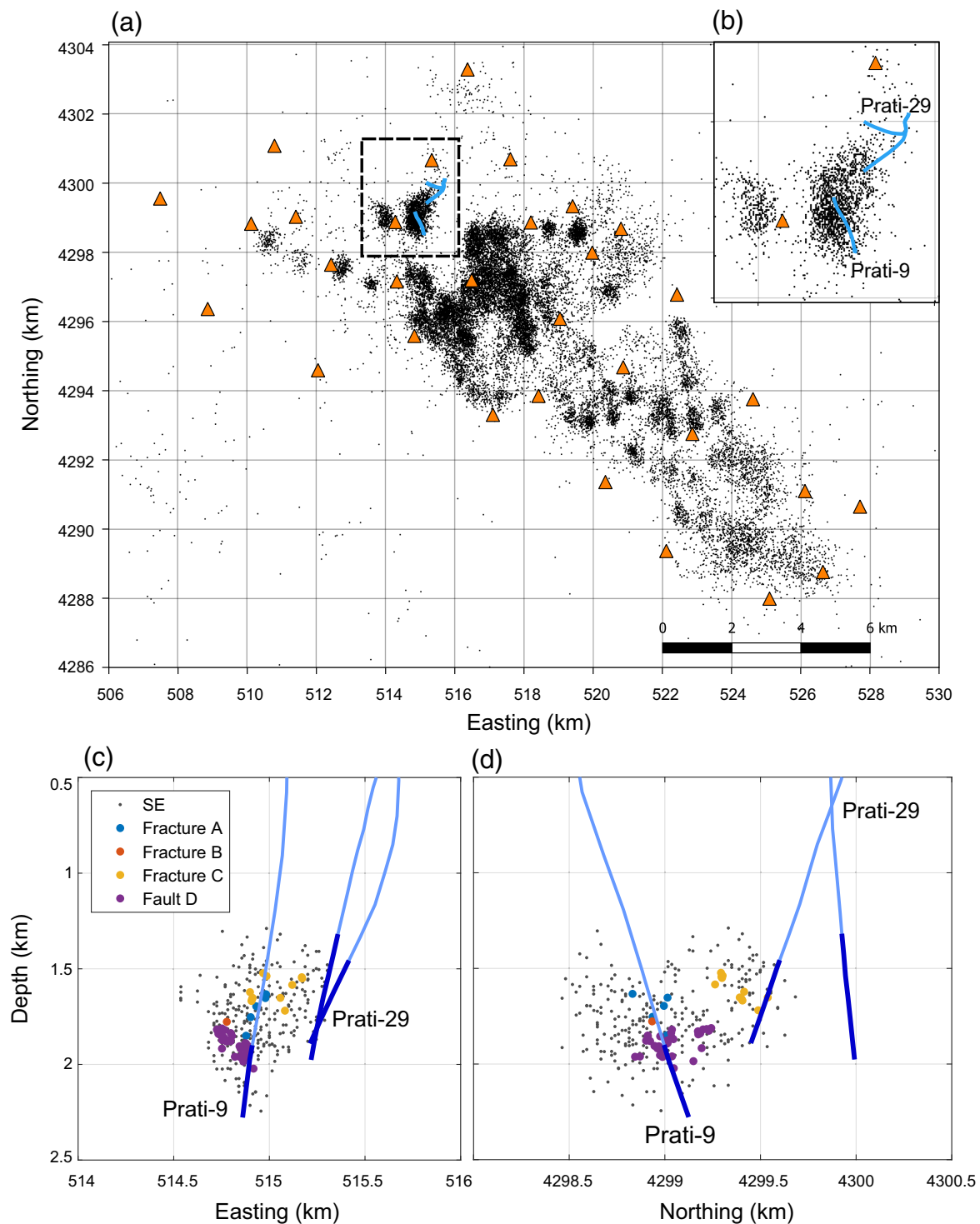
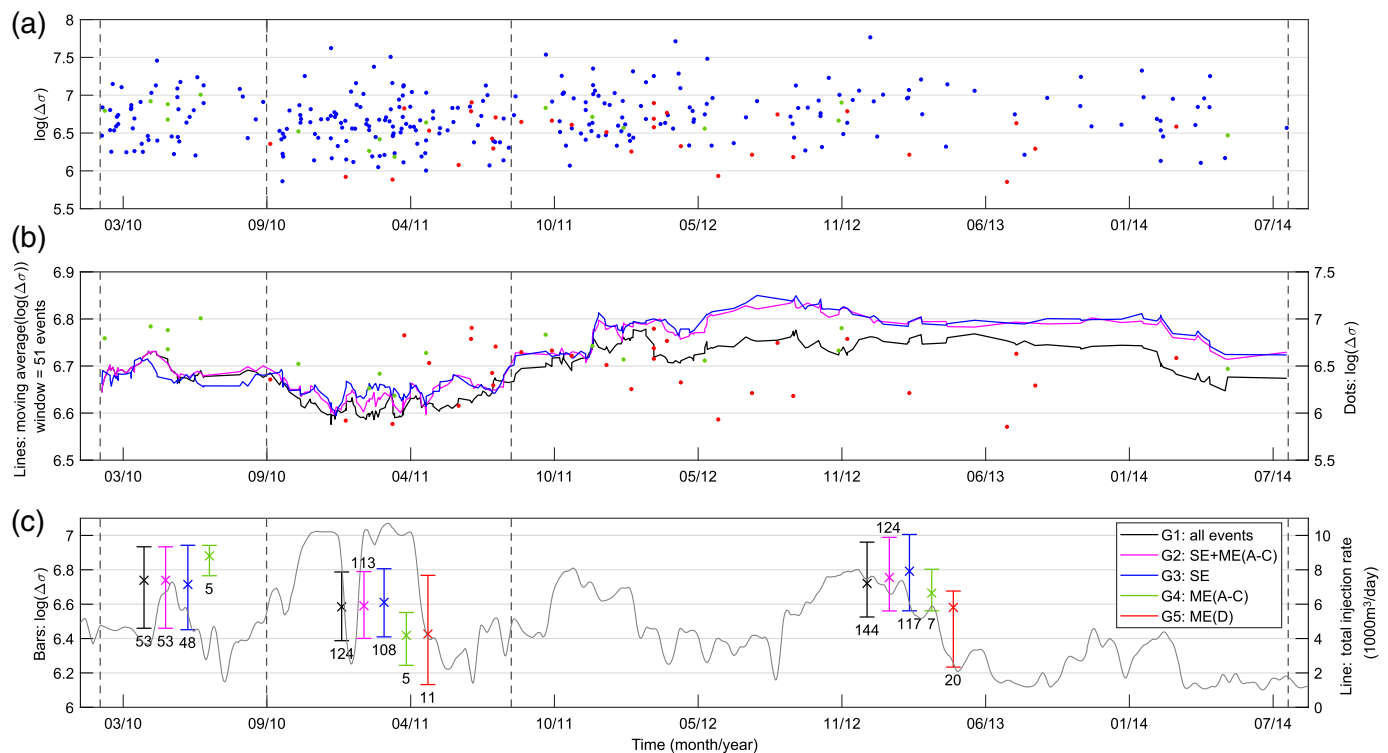


Figure 1. (a) Spatial distribution of seismicity recorded at The Geysers geothermal field between November 2007 and August 2014 according to the Northern California Earthquake Data Center (NCEDC) catalog (NCEDC, 2014). Seismic stations are represented by orange triangles. The study area is indicated roughly by the black-dashed square and shown in detail in panel (b). Thick solid blue lines indicate the trajectories of injection wells in the area of the analyzed seismicity cluster. (c,d) The locations of 321 seismic events analyzed in this study. “Multiple events” (ME), that is, events exhibiting high waveform similarity with at least two other events, are plotted as colored dots with the color

indicating the structures A–D distinguished by Staszek *et al.* (2021). The locations of ME were determined by double-difference relocation by Staszek *et al.* (2021). “Single events” (SE), that is, all the remaining events not classified as ME, are plotted as gray dots, and their locations come from the catalog provided by NCEDC (NCEDC, 2014). Trajectories of injection wells are marked with blue and their open-hole sections with dark blue. As visible in the plots, Prati-29 injection well has two separate endings. The color version of this figure is available only in the electronic edition.



0.9 S-wave velocity. More details concerning the estimation of stress-drop values and their uncertainties can be found in [Kwiatek et al. \(2015\)](#) and [Staszek et al. \(2017\)](#), their Texts S1 and S4 in the Supporting Information). Estimated stress-drop values fell in the range 0.7–58.3 MPa with a median value of 4.7 MPa.

The groups of SE and ME were distinguished by [Staszek et al. \(2021\)](#) based on the results of signal similarity analysis. Among the events with calculated static stress-drop values, the number of events in each group is the following: SE: 273 events, ME delineating the fractures A–C: ME(A–C): 17 events, ME delineating the fault D: ME(D): 31 events. Figure 1 presents the locations of analyzed 321 seismic events. For SE, the original locations provided by the Northern California Earthquake Data Center ([Northern California Earthquake Data Center \[NCEDC\], 2014](#)) are plotted, and for ME the locations obtained after double-difference relocation by [Staszek et al. \(2021\)](#) are visualized.

Injection operations into Prati-9 and Prati-29 wells started in November 2007 and April 2010, respectively. Injection into Prati-29 finished in June 2013, whereas Prati-9 was active till the end of the analyzed time period, that is, August 2014. For this entire time period, daily injection rates to both wells are available due to courtesy of Calpine Corporation, Patricia Martínez-Garzón, and Grzegorz Kwiatek, and can be downloaded via EPISODES Platform (see [Data and Resources; IS EPOS, 2017](#)). Injection into both wells was performed in seasonal cycles with peak injection rates occurring during winter months (Fig. 2c). The TIs established by [Staszek et al. \(2017\)](#) cover the following time periods: (1) 1 February 2010 to 13 September 2010 with median injection rate value into both wells equal to 4501 m³/day, (2) 23 September 2010 to 21

Figure 2. Temporal changes of $\log(\Delta\sigma)$ of seismic events within groups 1–5 (G1–G5): (a) mean $\log(\Delta\sigma)$ of the events from groups 3–5. Groups 1 and 2 are not plotted separately as $G1 = G3 + G4 + G5$ and $G2 = G3 + G4$; (b) moving average of $\log(\Delta\sigma)$ of events from groups 1–3 calculated in 51-event window (lines) and mean $\log(\Delta\sigma)$ of the events from groups 4 and 5 (dots); and (c) statistics of $\log(\Delta\sigma)$ values in time intervals (TIs) 1–3 for groups 1–5. Crosses indicate median $\log(\Delta\sigma)$ values in each TI, bars present 25th and 75th percentiles of $\log(\Delta\sigma)$. Below or above each bar the number of events used for calculations is given. Gray-solid line represents the total injection rate into Prati-9 and Prati-29 injection wells. Tested TIs are separated with gray-dashed lines. All colors in panels (a) and (b) are consistent with the legend presented in panel (c). In the legend, ME stands for “multiple events,” that is, events exhibiting high waveform similarity with at least two other events. SE represents “single events,” that is, all the remaining events not classified as ME. Letters A–D indicate the structures distinguished by [Staszek et al. \(2021\)](#) and presented in Figure 1c,d. Structures A–C were classified as fractures and structure D as a fault. The color version of this figure is available only in the electronic edition.

August 2011 with median injection rate value equal to 6680 m³/day, (3) 28 August 2011 to 7 August 2014 with median injection rate value equal to 3915 m³/day.

Methods

To examine temporal and spatial stress-drop variability separately, we performed statistical assessment of $\log(\Delta\sigma)$ variations in the three TIs distinguished by [Staszek et al. \(2017\)](#) but in different groups of events. The groups consisted of events related to the activation of different types of structures: structures hosting

TABLE 1

Results of Testing Statistical Significance of $\log(\Delta\sigma)$ Changes Between Distinguished TIs for Groups 1–5 (G1–G5) with Wilcoxon Rank Sum Test (0, H_0 Not Rejected; 1, H_0 Rejected) and Corresponding p -Values

Group of Events: Description (Number of Events)	TI1–TI2: Test Result, p -Value	TI2–TI3: Test Result, p -Value	TI1–TI3: Test Result, p -Value
G1: All events (321)	1, 0.007	1, 2.09×10^{-4}	0, 0.840
G2: SE + ME from fractures (290)	1, 0.015	1, 3.28×10^{-5}	0, 0.320
G3: SE (273)	0, 0.070	1, 8.69×10^{-5}	0, 0.184
G4: ME from fractures (17)	Insufficient sample size	Insufficient sample size	Insufficient sample size
G5: ME from the fault (31)	No data in TI1	0, 1	No data in TI1

The null hypothesis (H_0) stated that the distributions of $\log(\Delta\sigma)$ in tested TIs have equal medians, implying no change in $\log(\Delta\sigma)$ between time periods. Test results in which H_0 was rejected are in bold. ME stands for “multiple events,” that is, events exhibiting high waveform similarity with at least two other events. SE represents “single events,” that is, all the remaining events not classified as ME. $\Delta\sigma$, static stress drop; TIs, time intervals; H_0 , null hypothesis tested by Wilcoxon rank sum test.

only SE, fractures, and the fault. By gradually removing the events related to specific structures from the full set of events and testing the statistical significance of $\log(\Delta\sigma)$ variations in each group, we could identify which activated structures exhibit temporal stress-drop variability and therefore are more affected by pore pressure changes. Simultaneously, the sample sizes remained sufficient for statistical testing to ensure the reliability of the results. The following groups of events were established: (1) G1: all events involved in the original analysis by Staszek *et al.* (2017; 321 events), (2) G2: SE and ME that did not occur along the identified fault D (SE+ME(A–C); 290 events), (3) G3: SE (273 events), (4) G4: ME that occurred along the fractures A–C (ME(A–C); 17 events), (5) G5: ME that occurred along the identified fault D (ME(D); 31 events). The significance of individual groups is as follows: (1) G1: a reference group, (2) G2: group representing all activated structures except for the fault, (3) G3: group representing the structures hosting only SE, (4) G4: group representing the fractures, (5) G5: group representing the fault. The proposed division into groups 1–5 was adopted because spatially isolated ME delineating the fault (G5) are characterized by significantly lower $\Delta\sigma$ than all other events (G2). The median values of $\Delta\sigma$ in groups 5 and 2 equal 3.4 and 4.8 MPa, respectively. What is more, it was observed by Staszek *et al.* (2021) that the seismicity rate of ME delineating the fault is inversely related to the injection rate variations, which stands in contradiction to the common trend represented by all the remaining events (see their fig. 3a,b). This fact could indicate that the response of the fault to injection is different from the response of other structures. Finally, it is important that individual evaluation of $\log(\Delta\sigma)$ variability in the group of ME delineating only the fractures (G4) would not be reliable due to very small sample sizes (5, 5, and 7 events in TI1, TI2, and TI3, respectively). Instead, the influence of ME from the fractures on the variability of stress drop was assessed by comparing the results of testing groups 2 and 3.

For testing temporal $\log(\Delta\sigma)$ variations, the Wilcoxon rank sum test was used, with the null hypothesis (H_0) stating that the

distributions of $\log(\Delta\sigma)$ in tested TIs have equal medians. This implies no change in $\log(\Delta\sigma)$ between tested time periods. The test was applied at 5% significance level for H_0 rejection. This means that if the p -value obtained from the test is less than 0.05, the null hypothesis is rejected, indicating that there is a statistically significant difference between the medians of $\log(\Delta\sigma)$ in tested groups. The lower the p -value the stronger the evidence against the null hypothesis, implying that the observed differences are highly unlikely to have occurred by chance. For the calculations, mean $\log(\Delta\sigma)$ value for each event was used, as described in Staszek *et al.*, 2017 (their Text S4 in the Supporting Information). Moreover, to test the influence of stress-drop estimation uncertainties on the results, the Wilcoxon rank sum test was performed 1000 times using synthetic $\log(\Delta\sigma)$ series. Synthetic $\log(\Delta\sigma)$ series were generated by randomly choosing $\log(\Delta\sigma)$ values on the basis of probability density functions estimated separately for each seismic event.

Results

The results of testing stress-drop variability in groups 1–5, obtained using mean $\log(\Delta\sigma)$ value for each seismic event, are presented in Table 1. In addition, median $\log(\Delta\sigma)$ and $\Delta\sigma$ values for each group and each TI are given in Table 2. Finally, Table 3 presents the influence of stress-drop estimation uncertainties on the results by showing the number of trials, out of 1000 synthetic $\log(\Delta\sigma)$ series, in which the null hypothesis was rejected by Wilcoxon rank sum test.

Temporal stress-drop trends in groups 1–3

First, performed statistical analysis reveals that there is a significant change in $\log(\Delta\sigma)$ between TI1 and TI2 in groups 1 and 2 but not in the group 3 (Table 1). This means that the removal of ME related to the activation of fractures A–C from the group 2 results in losing the evidence for the rejection of the null hypothesis. However, the removal of only ME related to the activation of fault D from the full set of events (group 1) still allows for H_0 rejection. Therefore, it could be simply

TABLE 2
Median log ($\Delta\sigma$) and $\Delta\sigma$ Values in Distinguished TIs for Groups 1–5 (G1–G5)

Group of Events: Description (Number of Events)	T11: Median log ($\Delta\sigma$), Median $\Delta\sigma$ (MPa)	T12: Median log ($\Delta\sigma$), Median $\Delta\sigma$ (MPa)	T13: Median log ($\Delta\sigma$), Median $\Delta\sigma$ (MPa)
G1: All events (321)	6.74 (53), 5.5	6.58 (124), 3.8	6.72 (144), 5.3
G2: SE + ME from fractures (290)	6.74 (53), 5.5	6.59 (113), 3.9	6.76 (124), 5.7
G3: SE (273)	6.72 (48), 5.2	6.61 (108), 4.1	6.79 (117), 6.2
G4: ME from fractures (17)	6.88 (5), 7.6	6.41 (5), 2.6	6.66 (7), 4.6
G5: ME from the fault (31)	No data in T11	6.43 (11), 2.7	6.58 (20), 3.8

The number of events is given in brackets, next to the median log($\Delta\sigma$) values. ME stands for “multiple events,” that is, events exhibiting high waveform similarity with at least two other events. SE represents “single events,” that is, all the remaining events not classified as ME. $\Delta\sigma$, static stress drop; TIs, time intervals.

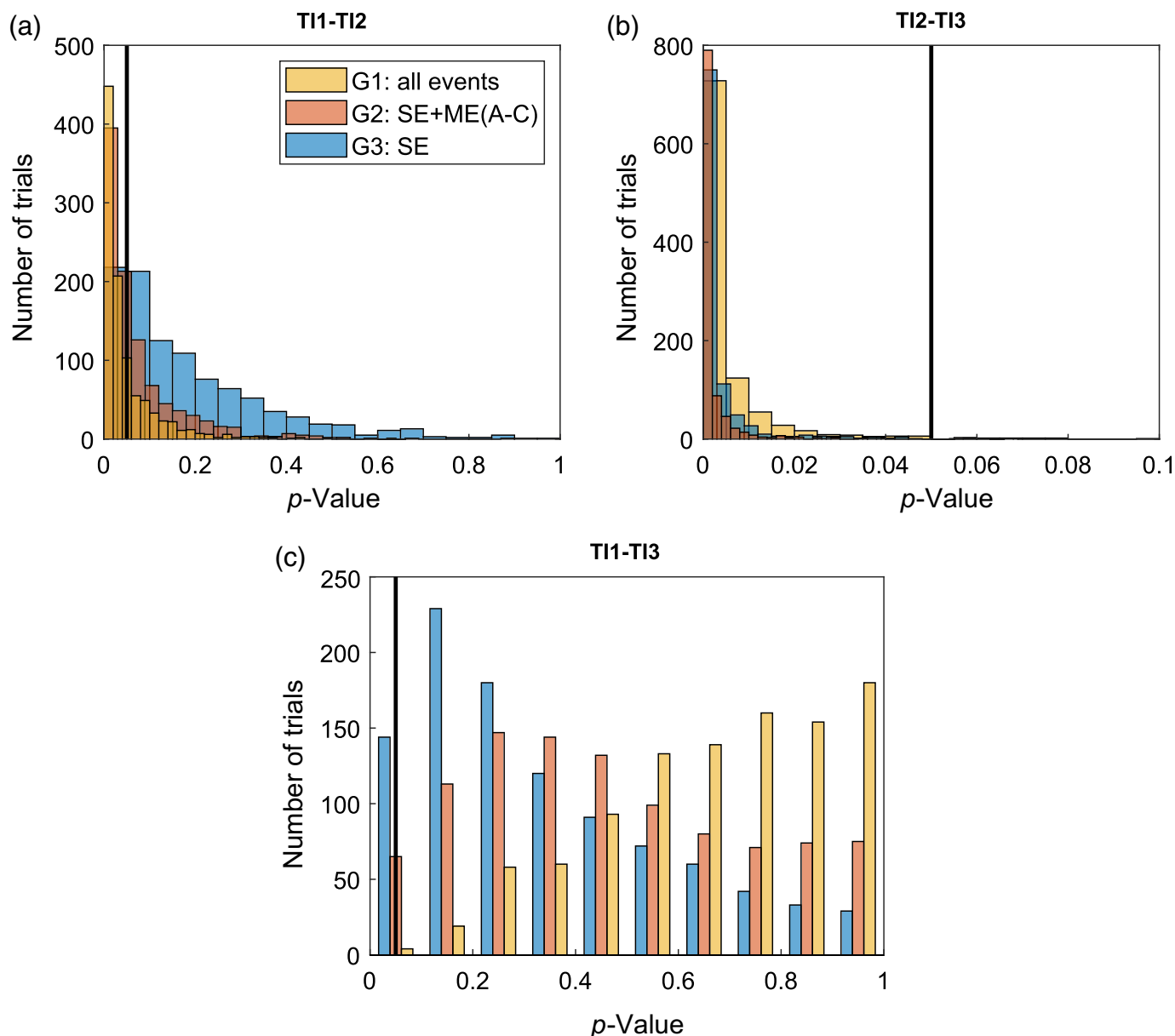
TABLE 3
Number of Synthetic log ($\Delta\sigma$) Series (Out of 1000) in Which Wilcoxon Test Confirmed Statistically Significant Difference in log ($\Delta\sigma$) Between Distinguished TIs for Groups 1–5 (G1–G5) and Corresponding Median p -Values from 1000 Trials

Group of Events: Description (Number of Events)	T11–T12 [X/1000], Median p -Value	T12–T13 [X/1000], Median p -Value	T11–T13 [X/1000], Median p -Value
G1: All events (321)	715, 0.024	986, 0.002	1, 0.694
G2: SE + ME from fractures (290)	558, 0.042	999, 4.02 × 10^{−4}	15, 0.426
G3: SE (273)	218, 0.128	994, 8.16 × 10^{−4}	53, 0.269
G4: ME from fractures (17)	Insufficient sample size	Insufficient sample size	Insufficient sample size
G5: ME from the fault (31)	No data in T11	1, 0.726	No data in T11

The tested null hypothesis stated that the distributions of log($\Delta\sigma$) in tested TIs have equal medians, implying no change in log($\Delta\sigma$) between time periods. The median p -values below the 5% significance level are in bold. ME stands for “multiple events,” that is, events exhibiting high waveform similarity with at least two other events. SE represents “single events,” that is, all the remaining events not classified as ME. $\Delta\sigma$, static stress drop; TIs, time intervals.

suggested that ME related to the activation of fractures is the main factor responsible for significant change in log($\Delta\sigma$) between T11 and T12. However, in the bigger picture we observe that gradual removal of ME(D) and ME(A–C) from the full set of events blurs the difference in stress drop between T11 and T12, as reflected by gradually increasing p -values from 0.007 in group 1, to 0.015 (group 2) to 0.070 in group 3 (Table 1). Therefore, the events responsible for the significant difference in log($\Delta\sigma$) between T11 and T12 are ME related to both fractures and the fault. Specifically, the change in stress-drop variability between T11 and T12 within groups 1–3 can be attributed to two factors: (1) ME delineating the fault D, which exhibit significantly lower $\Delta\sigma$, start to occur during T12 and therefore undervalue the stress-drop median in group 1; and (2) ME delineating the fractures A–C, which exhibit exceptionally high stress-drop values in T11 and low stress-drop values in T12 (Table 2, Fig. 2), and enhance stress-drop differences in groups 1 and 2. Therefore, after excluding both ME(D) and ME(A–C) from the analysis (group 3), the difference in stress drops between T11 and T12 is not recognized as significant anymore (Table 1). The impact of both ME(D) and

ME(A–C) on the statistical results is also reflected in the results of uncertainty analysis (Table 3), which shows that the difference between T11 and T12 is the most stable in group 1 (the number of trials that confirm the statistically significant difference in log($\Delta\sigma$) medians is 715 out of 1000), less stable in group 2 (558 trials with confirmed significant log($\Delta\sigma$) difference), and not significant in most trials in group 3 (218 trials with confirmed significant log($\Delta\sigma$) difference). It is important that the number of ME(A–C) in T11 and T12 is 5 and 5 events, respectively. In case of ME(D) there are no events in T11, and there are 11 events in T12. Because ME constitute only a small part of tested samples, the differences in median values of log($\Delta\sigma$) between groups 1 and 3 in T11 and T12 are not big, what is observable in Figure 2. The median values of $\Delta\sigma$ in groups 1–3 in T11 equal 5.5, 5.5, and 5.2 MPa, respectively. In case of T12, the median values of $\Delta\sigma$ in groups 1–3 equal 3.8, 3.9, and 4.1 MPa, respectively (Table 2). Then, the smallest difference in median $\Delta\sigma$ between T11 and T12, still recognized as statistically significant, is 1.6 MPa (group 2). Second, the analysis shows that there is a significant change in log($\Delta\sigma$) between T12 and T13 in all groups 1–3 (Table 1).



What is interesting, the uncertainty analysis reveals that in groups 2 and 3 the $\log(\Delta\sigma)$ difference between TI2 and TI3 is even slightly more stable than in the reference group 1 (compare the number of trials with H_0 rejection in Table 3 and see Fig. 3b). This again results from the relatively low values of $\Delta\sigma$ of events delineating the fault, which undervalue the stress-drop median in TI3 of group 1. It is worth noting that the results of testing the difference in $\log(\Delta\sigma)$ between TI2 and TI3 are more stable than in the case of TI1 and TI2 (Table 3), possibly due to the relatively smaller sample size in TI1 than in TI2 and TI3 (Table 2). The median values of $\Delta\sigma$ in groups 1–3 in TI3 equal 5.3, 5.7, and 6.2 MPa, respectively (Table 2). Then, the smallest difference in median $\Delta\sigma$ between TI2 and TI3 recognized as statistically significant is 2.1 MPa (group 3).

Finally, performed tests show no significant difference in $\log(\Delta\sigma)$ between TI1 and TI3 in all groups 1–3. In conclusion, obtained results confirm that after excluding ME delineating

Figure 3. Histograms of p -values obtained after testing the difference in $\log(\Delta\sigma)$ between distinguished TIs in the 1000 synthetic $\log(\Delta\sigma)$ series created for groups 1–3 (G1–G3): (a) the results of testing the difference between TI1 and TI2; (b) the results of testing the difference between TI2 and TI3; and (c) the results of testing the difference between TI1 and TI3. The tests were performed to check the influence of stress-drop estimation uncertainty on the stability of obtained results. Black-solid lines represent 5% significance level for the rejection of null hypothesis (H_0). The H_0 stated that the distributions of $\log(\Delta\sigma)$ in tested TIs have equal medians, implying no change in $\log(\Delta\sigma)$ between time periods. In the legend, ME stands for “multiple events,” that is, events exhibiting high waveform similarity with at least two other events. SE represents “single events,” that is, all the remaining events not classified as ME. Letters A–D indicate the structures distinguished by Staszek *et al.* (2021) and presented in Figure 1c,d. Structures A–C were classified as fractures and structure D as a fault. The color version of this figure is available only in the electronic edition.

the fault, $\log(\Delta\sigma)$ of earthquakes still exhibit significant temporal variability, which is inversely related to the injection rate (Tables 1 and 2, Fig. 2). Therefore, we can state in the area of Prati-9 and Prati-29 injection wells independent spatial and temporal stress-drop variability can be observed.

Temporal stress-drop trend in group 5

Another important observation is the fact that the test does not recognize a significant difference in $\log(\Delta\sigma)$ between TI2 and TI3 in group 5 (Tables 1, 3). This observation stays in contrast to the results obtained for all other tested groups 1–3, in which the difference between TI2 and TI3 is always recognized as significant. What is interesting, ME delineating the fault (group 5) exhibit also a contradictory behavior to SE and ME(A–C) in terms of activity in relation to the injection rate variations. It was shown by Staszek *et al.* (2021) that ME(D) exhibit higher activity during low-injection periods (fig. 3 in Staszek *et al.*, 2021). In contrast, both SE and ME(A–C) occur in bigger numbers during high-injection periods, as described in many previous injection case studies (e.g., Majer *et al.*, 2007; Leptokaropoulos *et al.*, 2018; Martínez-Garzón *et al.*, 2018). However, it should be noted here that the sample sizes in group 5 are very small, as they equal 11 and 20 in TI2 and TI3, respectively. Having all these facts in mind, we decided to investigate whether the observed lack of stress-drop change between TI2 and TI3 in the group 5 can be treated as a reliable result.

For this purpose, we created 1000 bootstrap samples of the size of 11 and 20 events from TI2 and TI3, respectively, in groups 1–3. The results of statistical testing are very stable in these groups (Table 3), so we decided to use them to check in how many trials, out of 1000, the significant difference in $\log(\Delta\sigma)$ will be recognized while having such a small number of data samples. We assumed that if the number of trials with recognized $\log(\Delta\sigma)$ difference will be relatively big, then the $\log(\Delta\sigma)$ trend in group 5 can be treated as a reliable result and further interpreted. With this method we obtained the following results: 211 trials with recognized significant difference in $\log(\Delta\sigma)$ between TI2 and TI3 in group 1, 317 trials in group 2, and 262 trials in group 3. The corresponding *p*-value histograms are presented in Figure 4. With these results, we concluded that, because of too few sample sizes in group 5, we cannot draw any reliable conclusion on the stress drop trend within this group. It would be interesting to check whether the temporal behavior of stress drop is structure dependent, but it requires a bigger data set.

Summary of observations

Summarizing, the most important observations are the following:

1. temporal stress-drop variability, identified originally by Staszek *et al.* (2017), remains statistically significant after excluding the ME delineating the fault (compare groups 1 and 2);
2. significant difference in stress drop between TI1 and TI2 results from the occurrence of ME delineating both fractures and the fault (compare groups 1–3 in Table 3);
3. the difference in stress drop between TI1–TI2 and TI2–TI3 is much better expressed by the ME delineating the fractures than by SE (compare groups 2 and 3 in Table 3 and groups 3 and 4 in Table 2); and
4. it is not possible to make reliable conclusions concerning the temporal stress-drop behavior within the group of ME delineating the fault due to insufficient data available.

Discussion

In the general picture, the results presented earlier imply that static stress drop is a parameter that reflects the strength of the discontinuities, and it is related to both (1) the intensity of the physical process responsible for earthquake generation (in this case pore pressure change), and (2) the structure of the reservoir. The statistical significance of temporal stress-drop variability, confirmed after the exclusion of the events related to the fault, demonstrates that the process of pore pressure change does influence static stress-drop values, regardless of the spatial heterogeneity of the reservoir. The relation between stress drop and effective normal stress, directly dependent on the pore pressure, was already suggested in several observational (Goertz-Allmann *et al.*, 2011; Lengliné *et al.*, 2014; Yoshida *et al.*, 2017) and laboratory (McLaskey *et al.*, 2014) studies. This conclusion is further supported by the fact that the difference in stress drop between TIs is better expressed by the ME delineating the fractures than by SE (Tables 2, 3). The events that occur repeatedly on the same structure reflect the differences in pore pressure better than the group of all SE, in which the impact of pore pressure change is blurred over many different structures, potentially having various “basic” stress-drop levels depending on, for example, rock damage level (Zhang and Sanderson, 2001; Kwiatak *et al.*, 2011; Yu *et al.*, 2020) or fault maturity (Zielke *et al.*, 2017).

The structure dependence of stress drop is reflected by the lower stress-drop values of ME delineating the fault, as described by Staszek *et al.* (2021). This fact could be interpreted as an image of a well-developed damage zone along the fault and the lower strength of the reservoir there (Zhang and Sanderson, 2001; Kwiatak *et al.*, 2011; Yu *et al.*, 2020). However, when interpreted within the context of other observations, it might also suggest the presence of a different dominant physical process responsible for the generation of earthquakes on this structure. This is a plausible hypothesis in terms of the inverse relation between seismic activity and injection rate described on this fault (see figure 3b in Staszek *et al.*, 2021). This relation stays in contradiction to the direct relation represented by SE and remaining ME that occurred in the analyzed area, and also often described in injection-induced seismicity studies (Majer *et al.*, 2007; Martínez-Garzón *et al.*, 2014, 2018). Such a discrepancy could

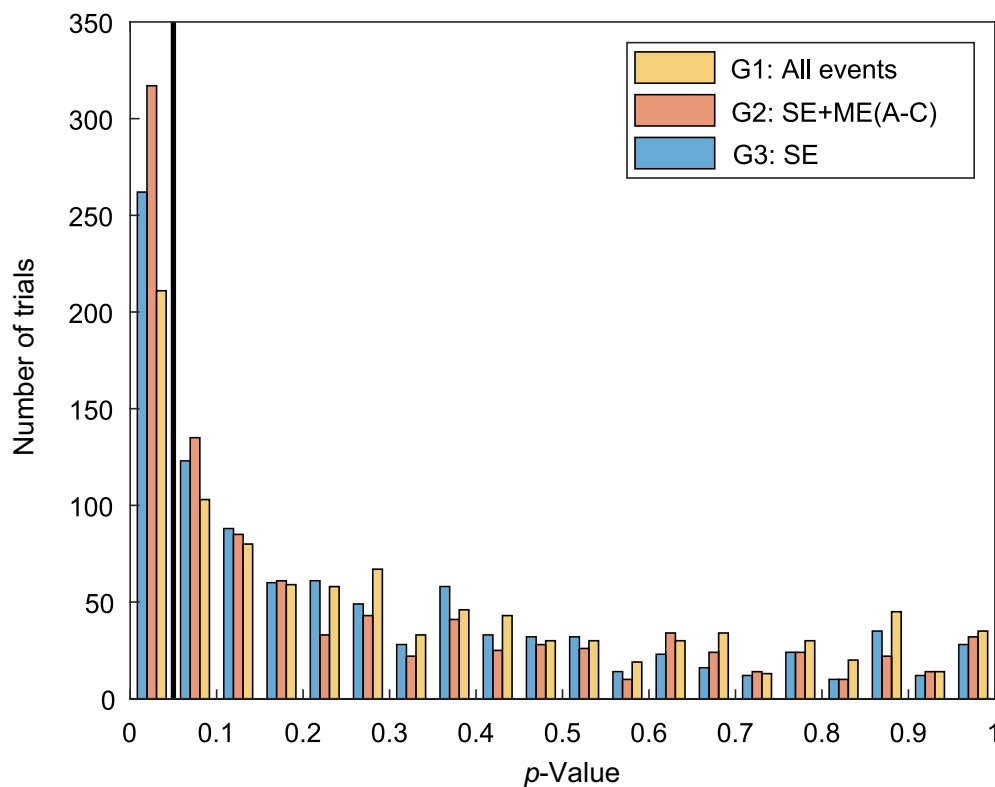


Figure 4. Histogram of p -values obtained after testing the difference in $\log(\Delta\sigma)$ between T12 and T13 in 1000 bootstrap samples driven from groups 1–3 (G1–G3). The tests were performed to check the reliability of statistical testing in group 5. Black-solid line represents 5% significance level for the rejection of null hypothesis (H_0). The H_0 stated that the distributions of $\log(\Delta\sigma)$ in tested TIs have equal medians, implying no change in $\log(\Delta\sigma)$ between time periods. In the legend, ME stands for “multiple events,” that is, events exhibiting high waveform similarity with at least two other events. SE represents “single events,” that is, all the remaining events not classified as ME. Letters A–D indicate the structures distinguished by Staszek et al. (2021) and presented in Figure 1c,d. Structures A–C were classified as fractures and structure D as a fault. The color version of this figure is available only in the electronic edition.

suggest that the fault is influenced by some other dominant factor than the structures responsible for SE occurrence and fractures A–C. Staszek et al. (2021) widely discuss the possibility of aseismic slip occurrence on the fault and even the interchanging seismic and aseismic behavior of the fault in time. Such a hypothesis is probable and supported by the fact that the fault generates a significantly bigger number of ME than the rest of the reservoir. Moreover, lately Chen et al. (2024) showed that aseismic slip could contribute to the lowering of the fault strength and therefore lead to the occurrence of earthquakes with lower stress drops. Staszek et al. (2021) discuss also the potential influence of poroelastic and thermoelastic stresses and orientation of the structures on observed spatial stress-drop variability. However, regardless of the main reason for stress-drop variability in this case, we suggest that it is a parameter that should be interpreted in the frame of specific structures. This suggestion is consistent with the results of Zielke et al. (2017), who concluded that there is a relation between fault maturity and static stress drop. In the context of their results, the analyzed fault D may be considered as

a smooth, mature fault generating seismic events with relatively lower stress-drop values.

Conclusions

The statistical analysis performed within this work confirms that pore pressure changes do influence static stress drop of earthquakes in the area of Prati-9 and Prati-29 injection wells, regardless of the spatial heterogeneity identified within the reservoir. However, it is shown that both pore pressure changes and the structure of the reservoir contribute to the temporal variations of static stress drop, and the individual impacts of these factors can be separated. Therefore, it is important to consider both spatial and temporal components simultaneously when analyzing the variability of static stress drop of injection induced earthquakes. Because static stress drop is a parameter influenced by both the structure of the reservoir and the intensity of dominant physical process responsible for the generation of earthquakes, we suggest that

it should be interpreted in the frame of specific structures.

Data and Resources

Raw injection data, well paths, seismic catalog and calculated source parameters are available via EPISODES Platform: <https://episodeplatform.eu> (last accessed December 2024; IS EPOS, 2017; Leptokaropoulos et al., 2019; Orlecka-Sikora et al., 2020) after registration and providing affiliation. The locations of single events (SE) were accessed through the Northern California Earthquake Data Center (NCEDC), doi: 10.7932/NCEDC. Stress-drop uncertainties and the locations of multiple events (ME) come from published sources listed in the references.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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