Temporal changes of static stress drop as a proxy for poroelastic effects at The Geysers geothermal field, California

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Static stress drop of induced events in fluid injection environments

Literature:

- Δσ increase with distance from the injection well
  - Deep Heat Mining project in Basel, Switzerland (Goertz-Allmann et al., 2011)
  - Berlín geothermal field, El Salvador (Kwiatek et al., 2014)
- Δσ variations by factor of 300 for events which occured at the same location
  - Soultz-sous-Forêts geothermal reservoir (Lengliné et al., 2014)

We expect that Δσ of induced events can be related to injection rate changes, due to its direct impact on pore pressure state in the reservoir.

Data: NW part of The Geysers geothermal field, Prati-9 and Prati-29 injection wells area

322 events → static stress drop calculated with mesh spectral ratio technique (Kwiatek et al., 2015)

	322 events
M_w	1.03 – 3.37
Δσ	0.77 – 71.50 MPa
mean(Δσ)	7.16 MPa
log_{10}(Δσ)	5.88 – 7.75
Z	2.08 – 2.87 km
Time	01/02/2010 – 07/08/2014

- Correlation between seismic and injection activity (Martínez-Garzón et al., 2013, 2014; Leptokaropoulos et al., 2016)
- **Technological activities:**
  - Prati-9: Nov-2007 to Aug-2014
  - Prati-29: Apr-2010 to Jun-2013
  - Start of production: ca 10-Dec-2011

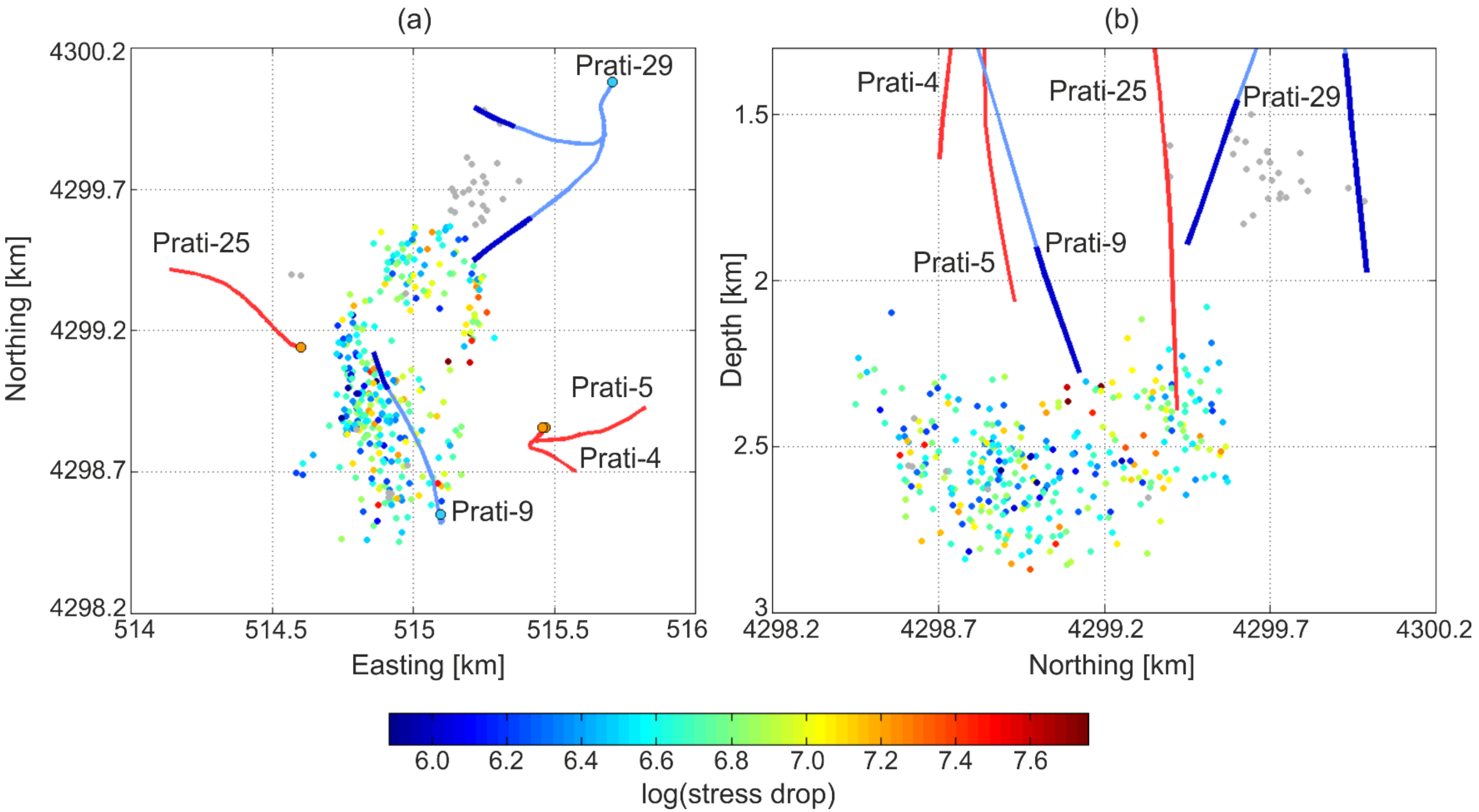

Figure 1. Spatial distribution of 322 seismic events used for the analysis in XY (a) and YZ (b) sections. Injection wells are plotted in blue, whereas production wells are marked with red. Open-hole sections of injection wells are marked with dark blue and thickened.

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Steps of the analysis

(1) Spearman correlation analysis between injection rates and decimal logarithm of static stress drop (log(Δσ))

(2) Examination of statistical significance of temporal changes of log(Δσ)

(3) Identification of factors responsible for observed significant temporal log(Δσ) variations

Parameters considered: **injection rates** (total, Prati-9 and Prati-29), **moment magnitudes**, **DC focal mechanisms**, **hypocentral depth**, **normalized distances** from open-hole sections of injection wells

(1) Spearman correlation analysis

Method:

- Spearman correlation analysis between injection rate values and log(Δσ) averaged over 11-79 events using moving average method (5% significance level)

Results:

- **significant negative correlation between total, Prati-9 and Prati-29 injection rates and log(Δσ) in the entire analyzed range of smoothing windows**
- depending on the well (Prati-9, Prati-29 or both), maximum absolute values of Spearman correlation coefficients were obtained for log(Δσ) smoothing event windows of 59, 50 and 49 events, respectively
- the strongest correlation was observed for injection rates into Prati-29 well

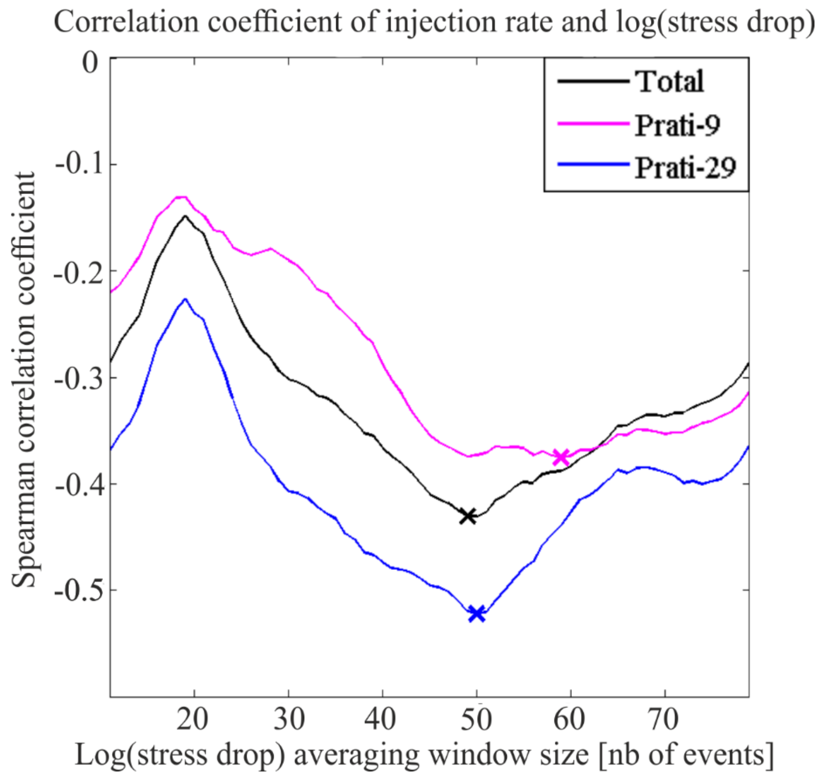

Figure 2. Spearman correlation analysis between injection rates and log(Δσ) smoothed in constant event windows. All correlation coefficient values presented are statistically significant at 5% significance level.

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(2) Examination of statistical significance of temporal changes of log(Δσ)

Method:

- comparison of medians and distributions of log(Δσ) between pairs of non-overlapping constant event windows (EWs) of 20-70 events shifted by 1 event
- pair of EWs which testing result is assigned to event ID = X_0: EW1 [X_0-EW, X_0-1] and EW2 [X_0+1, X_0+EW], for X_0>EW
- Statistical significance testing with non-parametric test at 5% significance level:
  - log(Δσ) medians: Wilcoxon rank sum (W) test
  - log(Δσ) distributions: two-sample Kolmogorov-Smirnov (KS) test

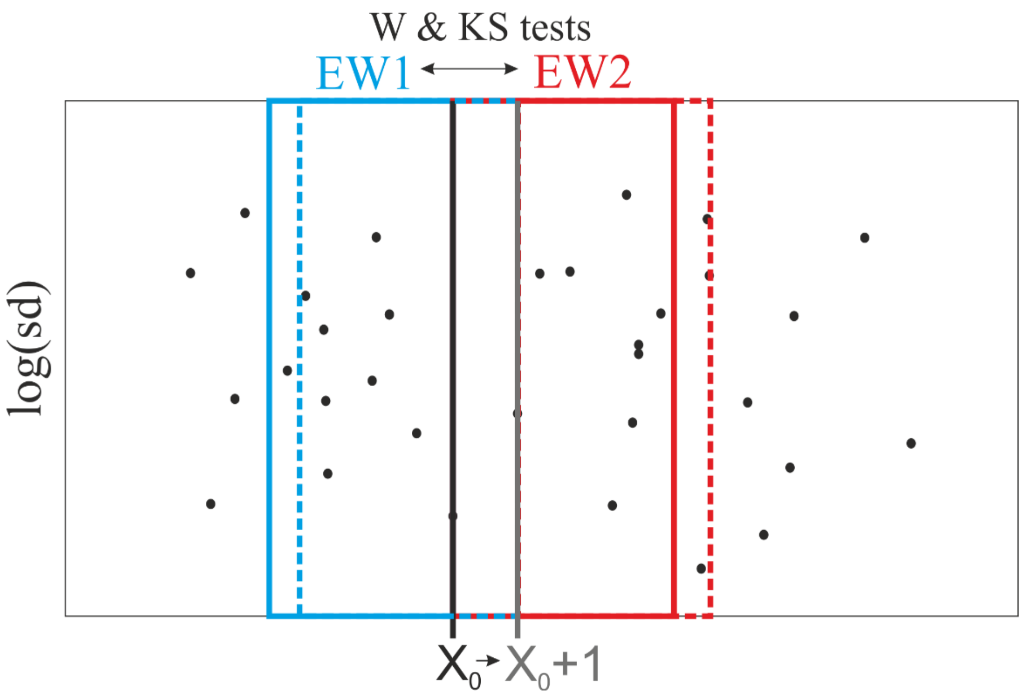

Figure 3. Method of testing statistical significance of temporal log(Δσ) changes in pairs of non-ovelapping constant events windows (EWs) shifted by 1 event.

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(2) Examination of statistical significance of temporal changes of log(Δσ)

Results:

- significant changes of log(Δσ) medians are recognized twice for EW=50: ca Sep-2010 and ca Sep-2011
- both recognized significant log(Δσ) changes can be observed over wide ranges of EWs by both statistical tests
- **three separate time intervals (TIs) can be distinguished on the basis of described temporal log(Δσ) changes**

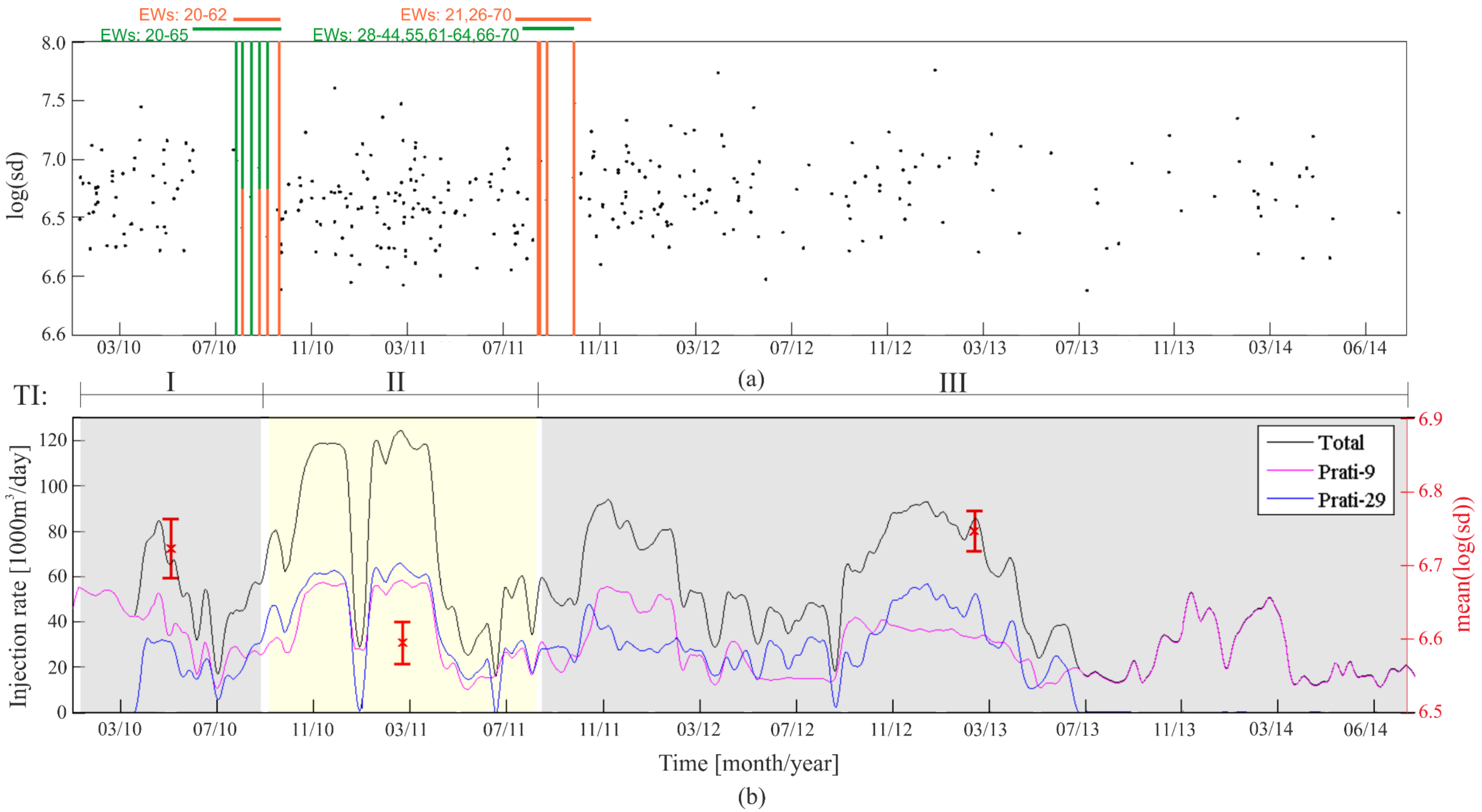

Figure 4. Significant temporal changes of log(Δσ) identified in 50-event windows (a) and injection rates variability in distinguished TIs (b).

(3) Identification of factors responsible for observed significant temporal log(Δσ) variations

Results:

- statistically significant changes of total and Prati-29 injection rates occur between adjacent TIs
- **trends of injection rates' changes are opposite to the trend of log(Δσ) changes**
- trends of other parameters changes cannot explain temporal log(Δσ) changes between distinguished TIs
- chi-squared test showed that there is no statistically significant change in the contents of normal, strike-slip and thrust faulting events between TIs

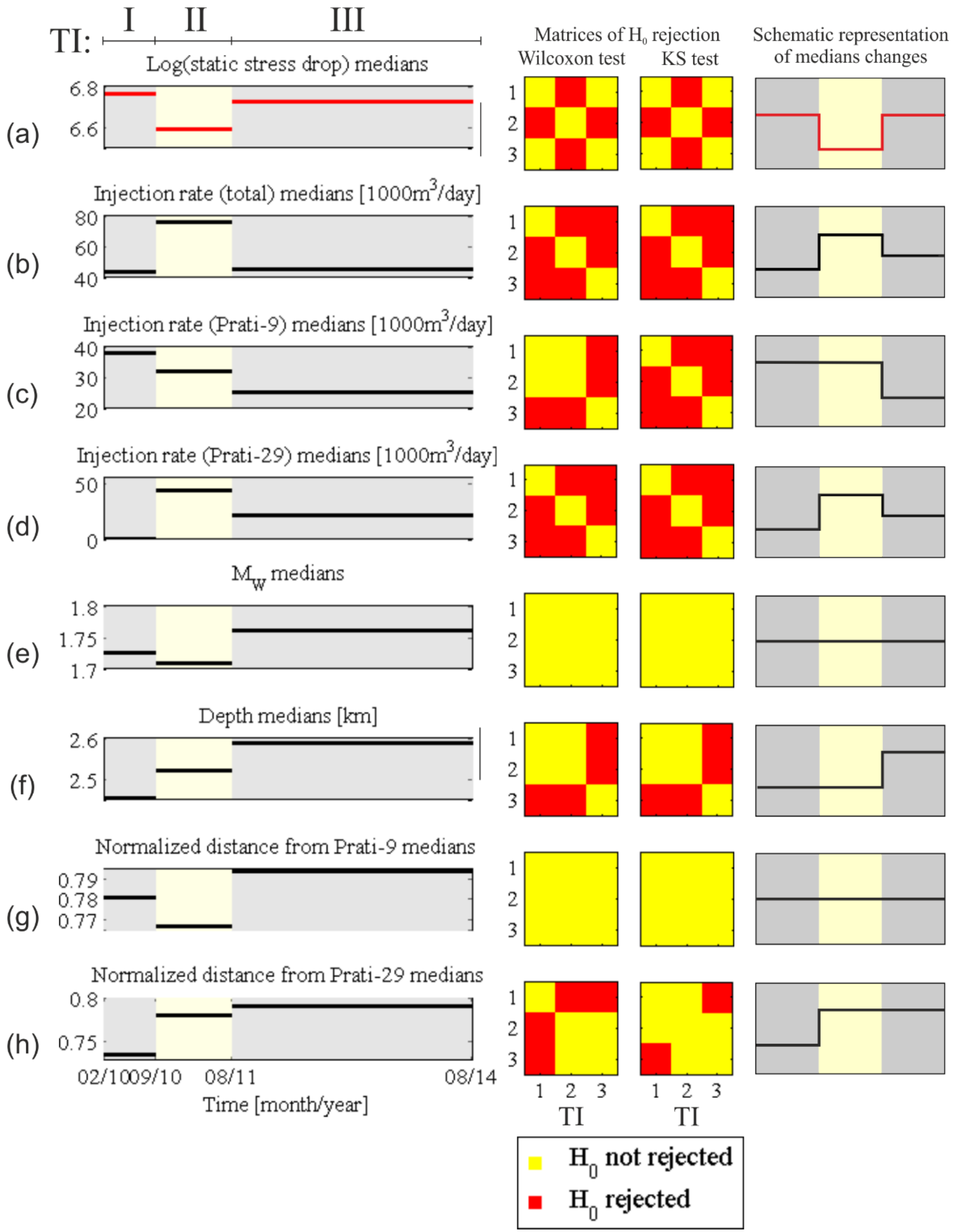

Figure 5. Analysis of the dependence of log(Δσ) temporal changes on other parameters' variations.

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Conclusions

(1) Observed variations of static stress drop in time are statistically significant.

(2) Significant temporal static stress drop variations are inversely related to injection rate fluctuations what strongly suggests that they are a result of pore pressure fluctuations and effective normal stress changes (Terzaghi, 1923).

(3) Observed significant changes of static stress drop distributions in time and their dependence on the operational phase implies the possibility to utilize static stress drop in seismic hazard assessment for NW part of The Geysers area (Staszek et al., 2016).

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Statistical significance of log(Δσ) changes due to Wilcoxon and Kolmogorov-Smirnov tests between pairs of 20-70 event windows

Table S1. The influence of stress drop estimation uncertainties on significant log(Δσ) changes recognition. Significant log(Δσ) changes which are the most resistant to stress drop estimation uncertainties, and therefore were used to distinguish TIs, are bolded.

Significant log(Δσ) change symbol	Range of event IDs (X_0)	Percentage of samples in which given significant log(Δσ) change (due to Wilcoxon test) was recognized at least once (out of total 1000 synthetic samples)	Percentage of samples in which given significant log(Δσ) change (due to Kolmogorov-Smirnov test) was recognized at least once (out of total 1000 synthetic samples)
A1/A2	31-33	39.0%	40.7%
B1/B2	55-67	94.2%	90.8%
E1/G2	177-194	95.5%	86.3%
G1/I2	270-281	68.7%	58.0%
H1	300-301	37.5%	32.8%

We did not consider other identified log(Δσ) changes in the main analysis as not reliable due to: (1) length of ranges of X_0 in which changes were identified equal 1, what suggests strong result instability (C1, D1, C2, E2, F2, H2, I2), (2) no changes visibility on log(Δσ) moving average curves, what suggests that they can be treated as an outliers of other X_0 ranges (F1, D2), (3) low temporal density of events in time periods of identified changes occurrence (G1, H1, I2), and (4) large changes susceptibility on stress drop estimation uncertainties (A1, A2, G1, I2, H1).

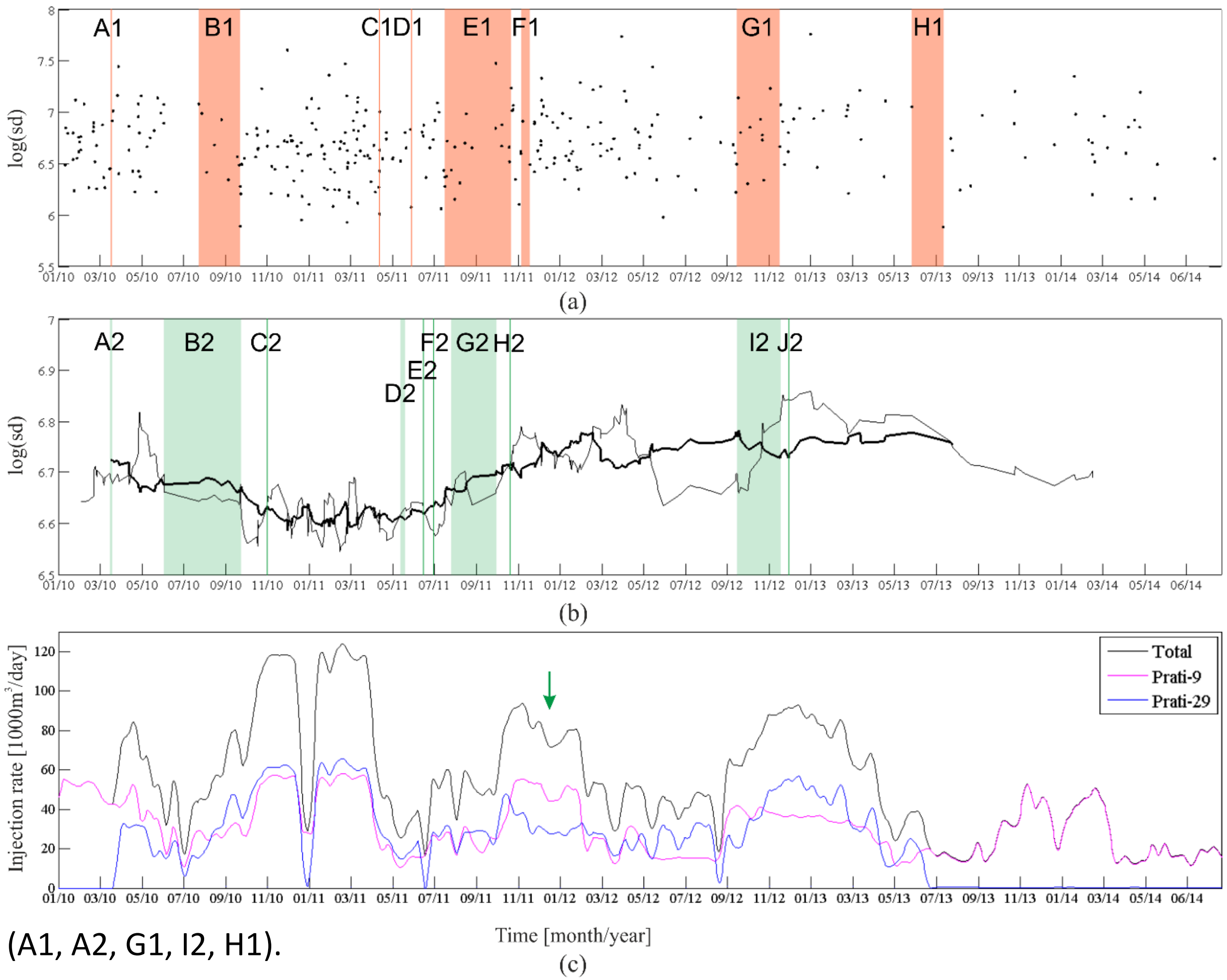

Figure S1. X_0 ranges of significant temporal log(Δσ) changes occurrence identified in 20-70 event windows by Wilcoxon (a) and Kolmogorov-Smirnov test (b), and injection rates variability in time (c). Black dots in subplot (a) represent log(Δσ) values for each event. In subplot (b) black solid lines present log(Δσ) values averaged over 51-event (thick line) and 25-event (thin line) symmetric window using moving average method.

Double-couple faulting mechanisms in TIs

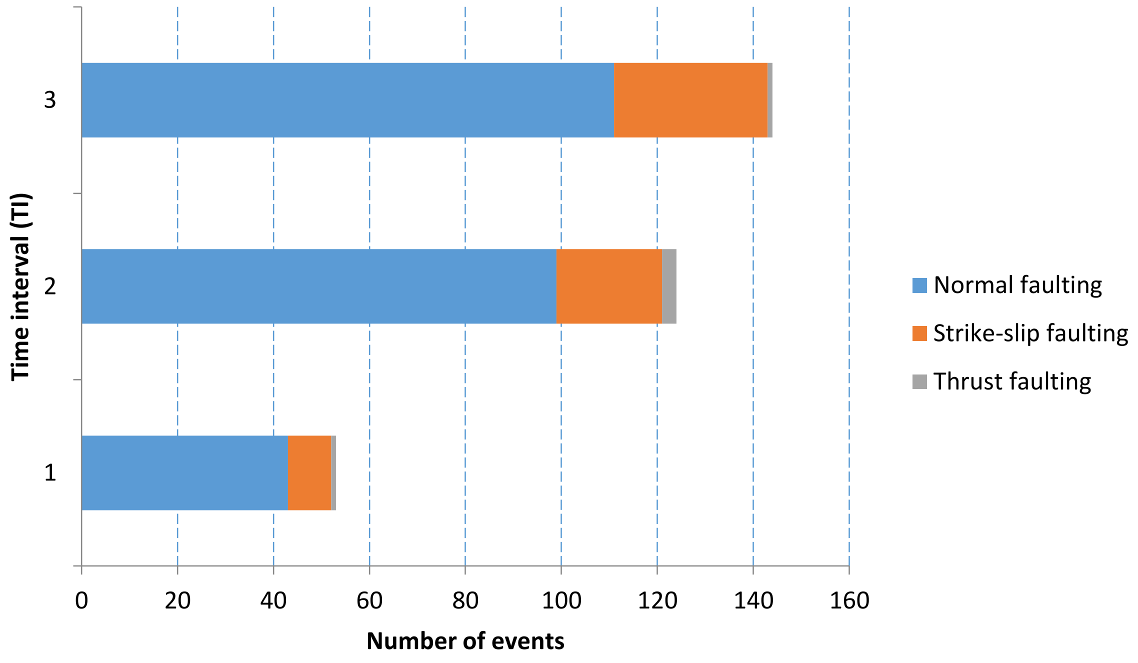

Figure S2. Content of faulting mechanisms in distinguished TIs.

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Examination of temporal changes of log(Δσ) in spatial seismicity clusters

Method:

- Assumption: events clustered in space occur in areas which have similar rock properties and level of damage
- Spatial seismicity clusters identified using k-means method (8 clusters distinguished in 1000 runs)
- Identification of log(Δσ) temporal changes in clusters > 30 events between 10-event non-overlapping windows ('internally varying' clusters)

Result:

- **in ca 94% of cases significant temporal log(Δσ) changes occur in at least one cluster among 8 distinguished**
- centroids of 'internally varying' clusters tend to group in the specific areas of entire seismicity cloud, what can suggest the existence of local geological structure or geomechanical properties differentiation within the reservoir, which promotes bigger injection rate gradients in specific areas

Table S2. Summary of the number of trials for which each possible number of 'internally varying' clusters was identified among 1000 runs.

Nb of 'internally varying' clusters	Nb of trials (log(Δσ) median change due to Wilcoxon rank sum test)	Nb of trials (log(Δσ) distribution change due to two-sample Kolmogorov-Smirnov test)
0	58	67
1	177	297
2	473	438
3	272	186
4	20	10
5	0	2
6	0	0
7	0	0
8	0	0

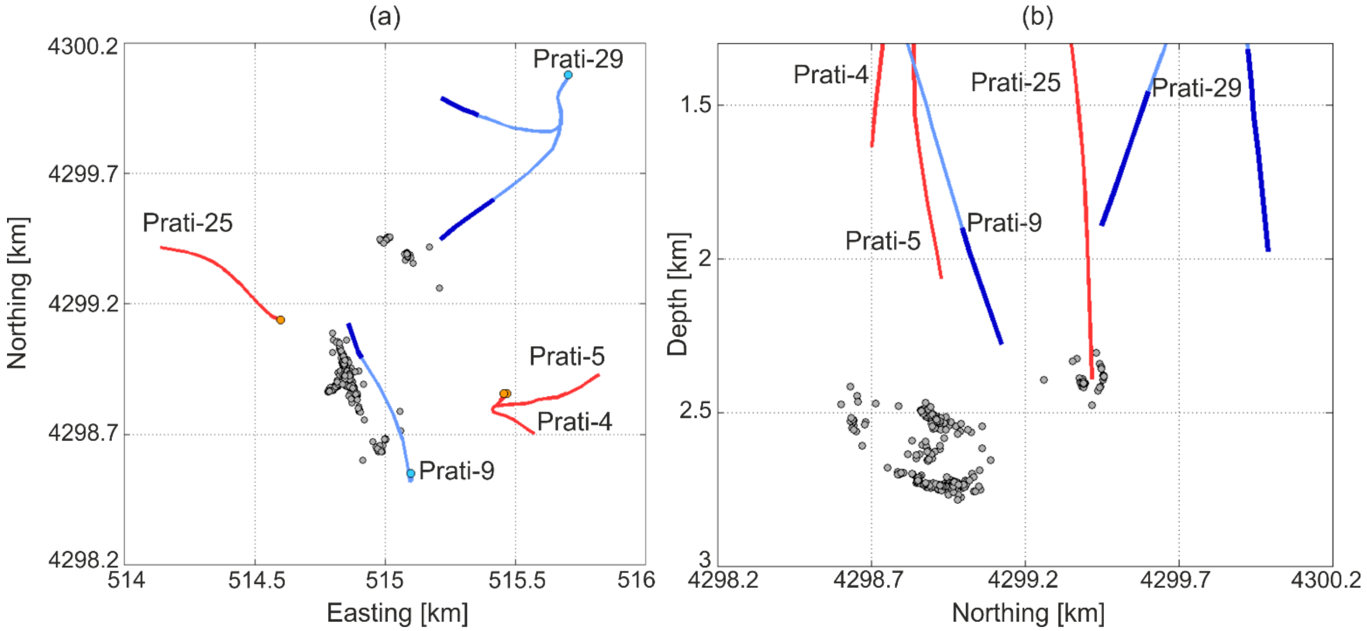
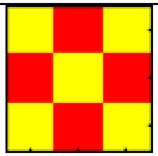
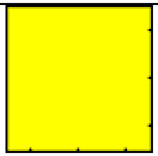
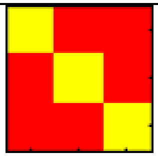
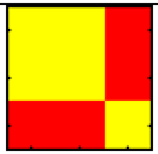
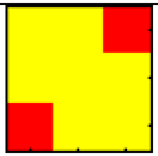
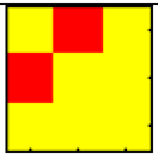
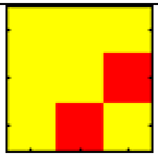
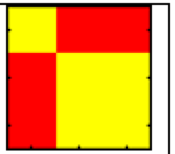


Figure S3. Localizations of centroids of 'internally varying' clusters identified using Wilcoxon rank sum test (gray dots) in XY (a) and YZ (b) sections.

Influence of log(Δσ) estimation uncertainties on obtained results

Table S3. Percentage values of outcomes obtained for each possible solution after testing 1000 synthetic log(Δσ) series. Solutions for which percentage value is higher than 12.5% are bolded.

Solution / Test	 (1)	 (2)	 (3)	 (4)	 (5)	 (6)	 (7)	 (8)
Wilcoxon test	**71.9%**	0.8%	0.1%	0.1%	0%	0.4%	**26.7%**	0%
Kolmogorov -Smirnov test	**51.4%**	7.7%	0.1%	0.2%	0%	3.8%	**36.6%**	0.2%

Result:

- **both log(Δσ) median and distribution changes patterns identified using mean values of log(Δσ) are the most probable solutions after considering log(Δσ) estimation uncertainties**
- log(Δσ) median changes pattern is more resistant to log(Δσ) uncertainties than the pattern of log(Δσ) distribution changes
- the second log(Δσ) change is much more resistant to log(Δσ) estimation uncertainties than the first one

Method:

- Estimation of probability density function of log(Δσ) for each event
- Generation of 1000 synthetic log(Δσ) series with log(Δσ) values chosen randomly on the basis of PDFs
- Wilcoxon rank sum and Kolmogorov-Smirnov tests performed on each series between distinguished Tis

Injection rate and static stress drop

- **Obtained results indicate that temporal log(Δσ) changes are related to injection rate changes** (Spearman correlation analysis + statistical significance analysis + uncertainty influence analysis)
- Increase of injection rate leads to the increase of pore pressure and consequently reduction of effective normal stress and reservoir strength (Terzaghi, 1923)

log(Δσ) changes may be related to effective normal stress changes

- Acoustic emission data (McLaskey et al., 2014)
- Soultz-sous-Forêts geothermal reservoir (Lengliné et al., 2014)
- Temporal changes in seismic activity correlated with injection activity (Martínez-Garzón et al., 2013; Leptokaropoulos et al., 2016)

- Alternative explaination: content of non-double-couple component in faulting mechanisms of seismic events (according to Fischer and Guest, 2011 tensile events exhibit low stress drops)