IAG-IASPEI, Kobe, Japan, 30.07 – 4.08.2017

Identifying pathways for gas and fluid migration caused by fracking processes, with the use of criteria defined in equivalent dimension phase spaces

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SHEER

SHale gas
Exploration and **E**xploitation
induced **R**isks

The European Union's Horizon 2020 research and innovation programme. Grant agreement No 640896.

Equivalent dimension (ED) approach

A seismic event can be characterised by a multitude of different parameters:

- Source parameters i.e.: t, lat, lon, $depth$, M, $[M_{i,j}]$, E_s $\Delta\sigma$, r_0 etc.
- Derived from the above i.e.: interevent time between this and the preceding event - τ, epicentral distance between this and the main shock - r, etc.
- Any other correctly defined.

The seismic event is a point in the parameter space, represented by the vector:

$$\mathbf{X} = [t, lat, lon, depth, M, [M_{i,j}], E_s\ \Delta\sigma, r_0, \ldots, \tau, r, \ldots, e_1, e_2, e_3, \ldots, I_1, I_2, I_3, \ldots, \ldots]$$

The parameters of seismic events:

1. are not comparable
2. the metric of most of them is non-Euclidean.

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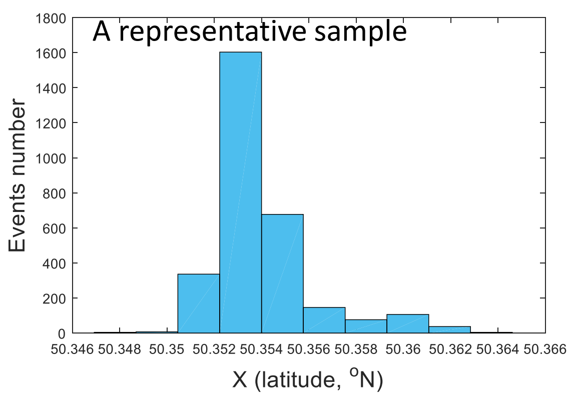
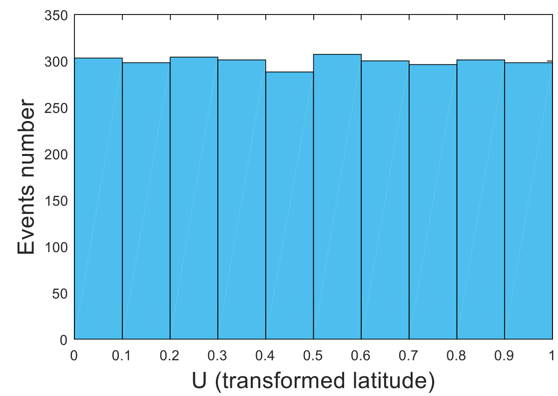
The concept of equivalent dimensions (Lasocki, GJI 2014)

Two intervals of the parameter values, $[x_{k,i},x_{k,j}]$, $[x_{l,s},x_{l,t}]$ are equivalent if $\Pr(X_k \in [x_{k,i},x_{k,j}]) = \Pr(X_l \in [x_{l,s},x_{l,t}])$. $U_k = F(X_k)$, where $F(\bullet)$ is the cumulative distribution, are **Equivalent Dimensions** of X_k

Every U_i is uniformly distributed in [0,1].



$$X_i \rightarrow U_i = F(X_i)$$



All U_i have Euclidean metric. The distance between the events k and l is $d(k,l) = \sqrt{\sum_{i=1}^{n} [U_i(k) - U_i(l)]^2}$

In general, F_{Xk}, are not known and are estimated by means of the non-parametric kernel estimation method. (e.g. Silverman, 1986)

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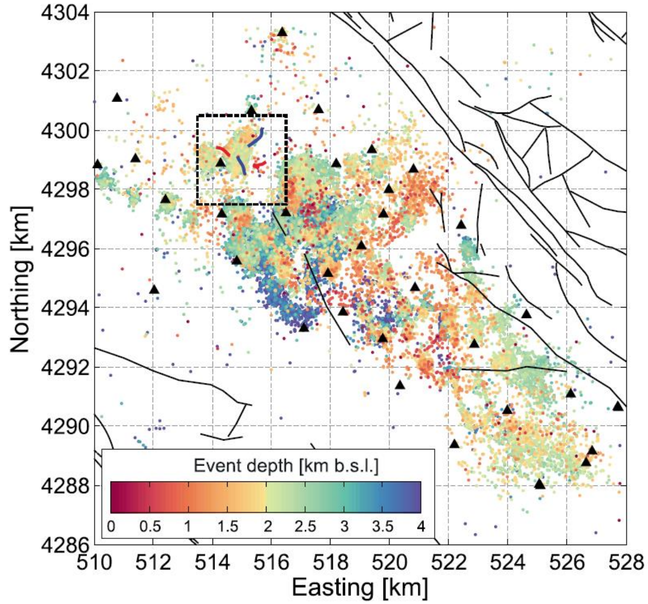
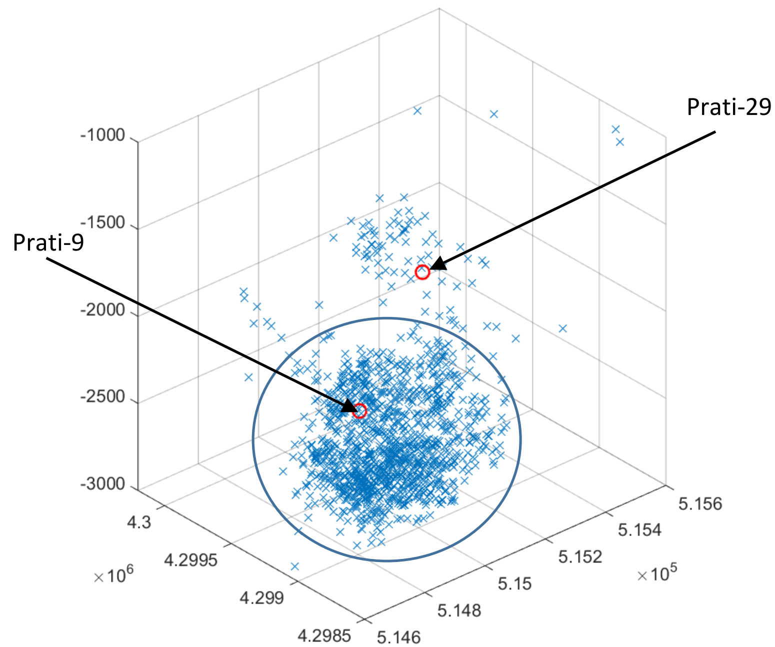
Data

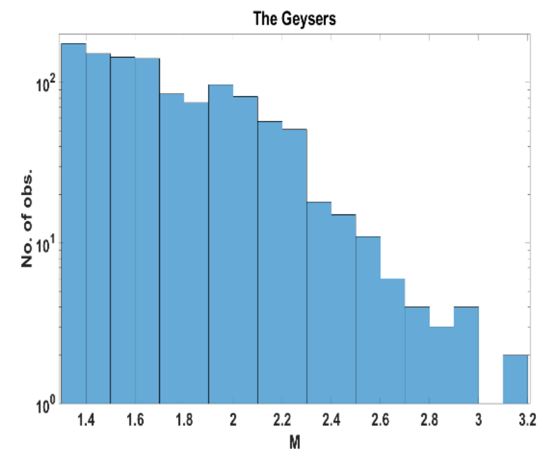
Seismicity occurred in the northwestern part of The Geysers geothermal field from Dec 2007 to Aug 2014.

Two injection wells: Prati-9 and Prati-29



Subcluster A – 1121 events from $M_{min} = 1.37$ to $M_{max}^{obs} = 3.16$





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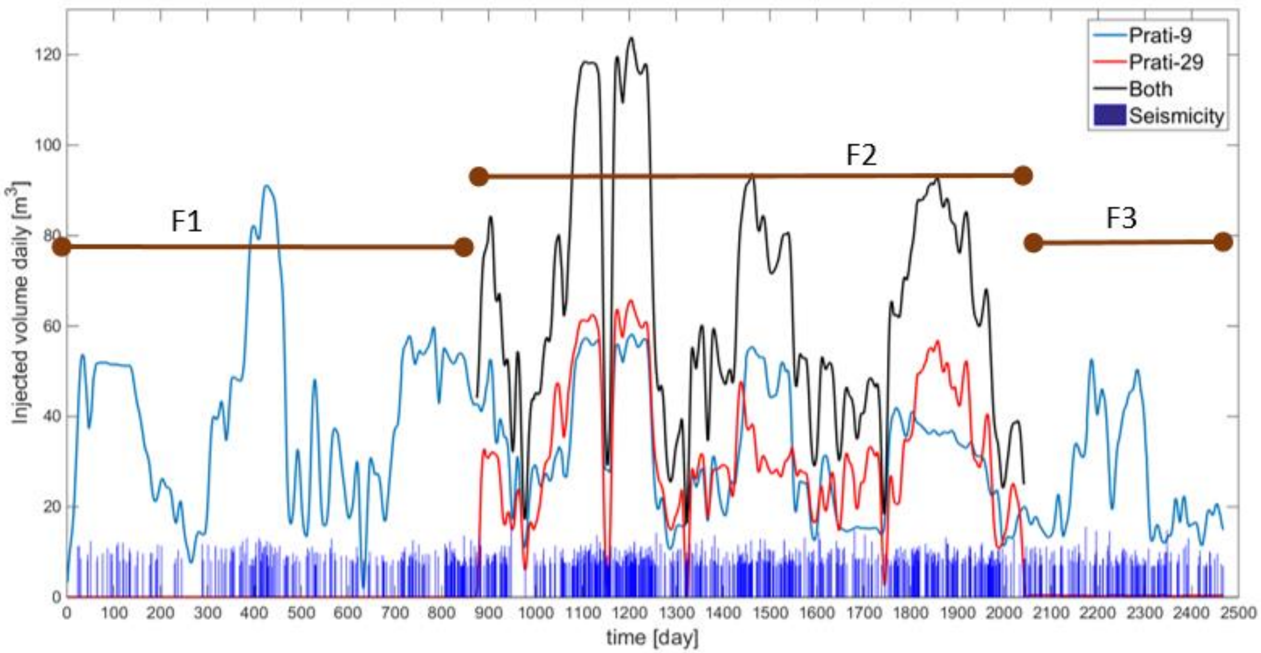
Data

Daily injected volumes into: Prati-9 (operating continuously) and Prati-29 (operating: Apr 2010 - Jun 2013)



Phase F1: Dec 2007 – Mar 2010, Injections only into Prati-9, <rate>=40 m^3/day, 248 EQ-s, λ=0.29 EQ/day

Phase F2: Apr 2010 – Jun 2013, Injections into Prati-9 and Prati-29, <rate>=65 m^3/day, 702 EQ-s, λ=0.60 EQ/day

Phase F3: Jul 2013 – Aug 2014, Injections only into Prati-9, <rate>=25 m^3/day, 171 EQ-s, λ=0.40 EQ/day

Data

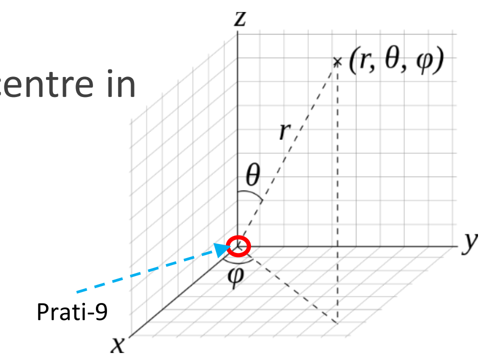
EQ-s parameters.

Original: Occurrence time: **t**, Hypocentre coordinates: **x, y, z**, Magnitude: M_w, FPS: strike ϕ, dip ρ, rake λ

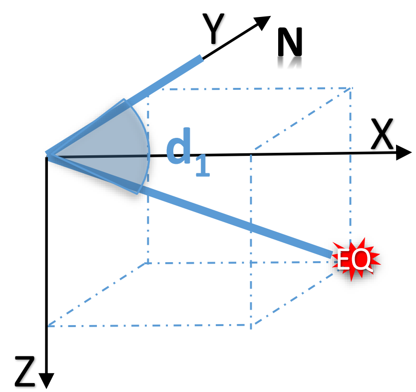
Derived:

dip_T , strike_T , dip_P , strike_P ;

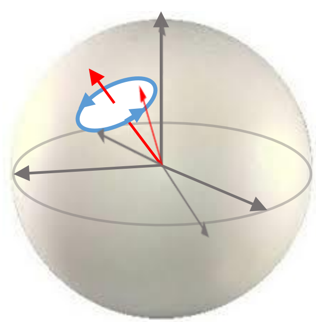
Spherical coordinates of hypocentre in the local system: **r, Θ, φ**

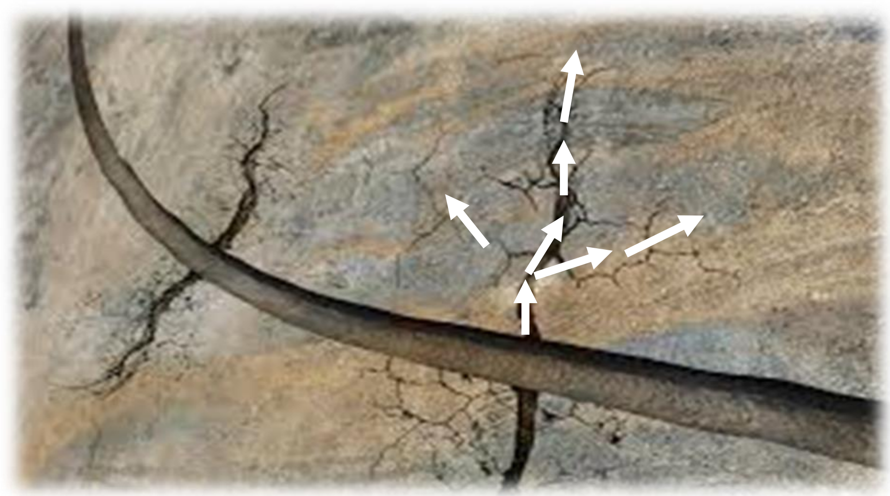


Deflection, d - the angle between the straight line connecting the hypocentre and NS direction



3D rotation, rot - the angle by which one double-couple (DC) earthquake source is turned into another arbitrary DC (Kagan, 2007)





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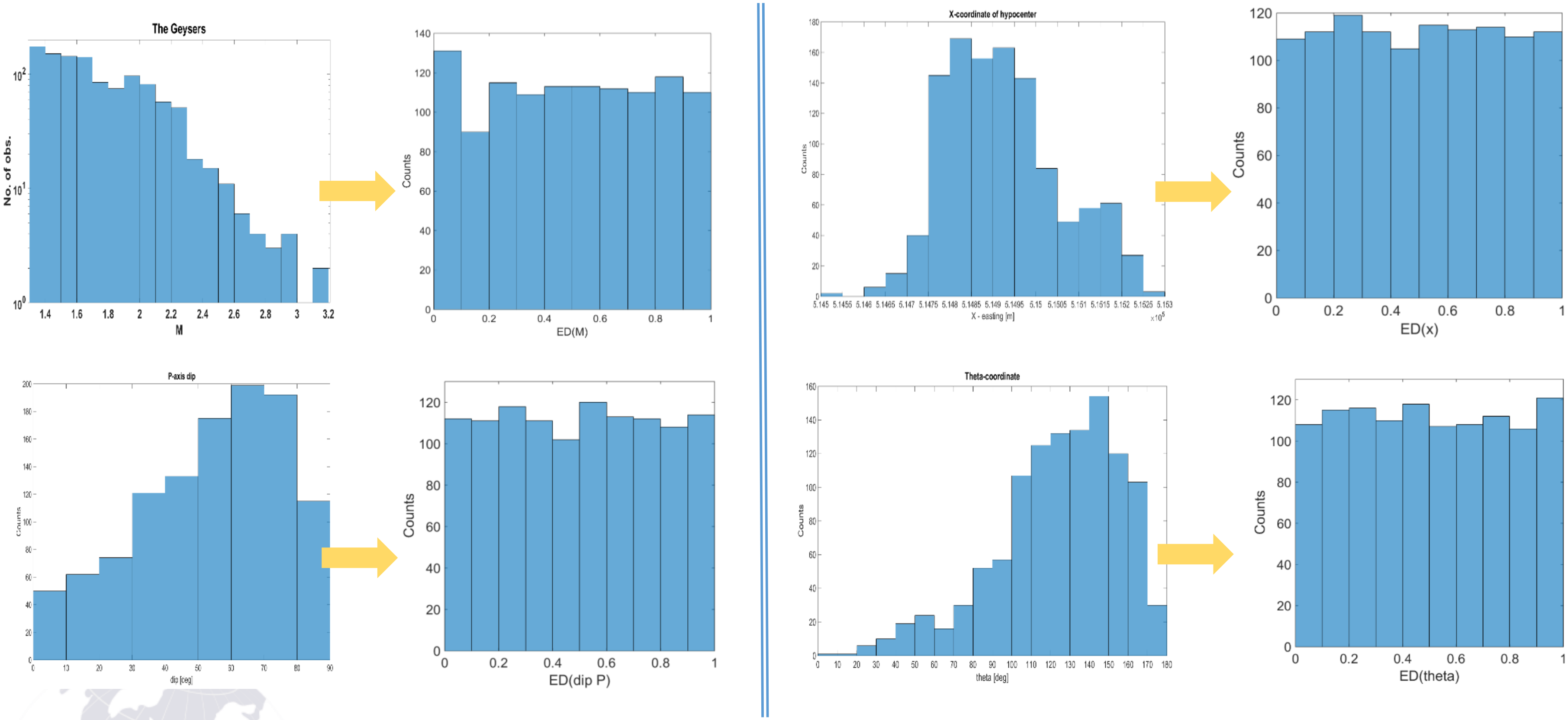
Data

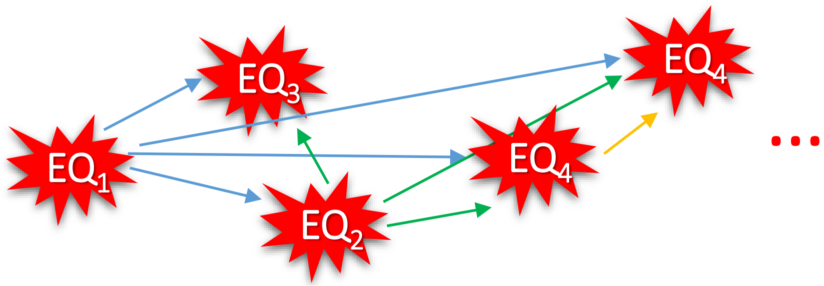
x, y, z, dip_T , strike_T , dip_P , strike_P , r, Θ, φ M_w , d, rot - transformed to Equivalent Dimensions

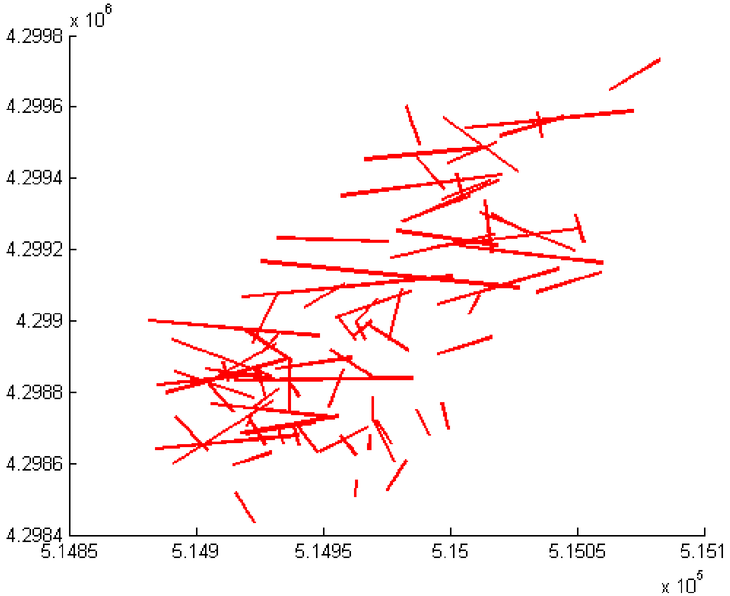


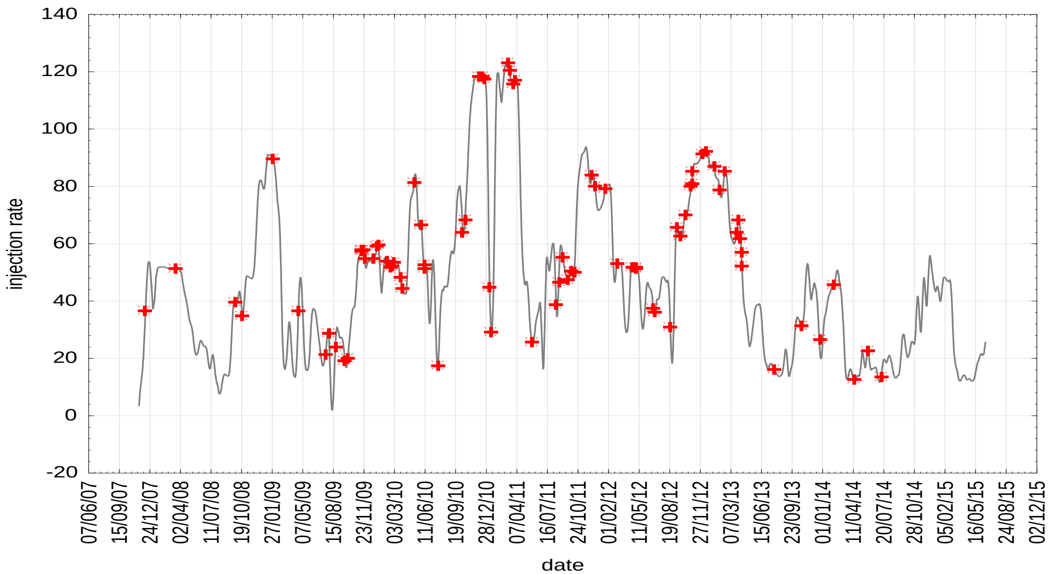
Extracting families of earthquakes:

$$l_{ik} = \sqrt{(d_i - d_k)^2 + (rot_i - rot_k)^2}$$

The distance between events in chosen space of parameters, l_{ik}, is an indicator of a growth of fracture network – *the smaller l_{ik} the stronger link between EQ_i and EQ_k. Criterion for family:* $l_{ik} \leq 0.2$







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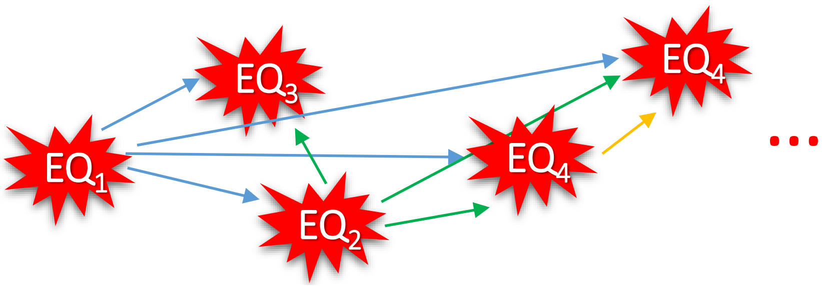

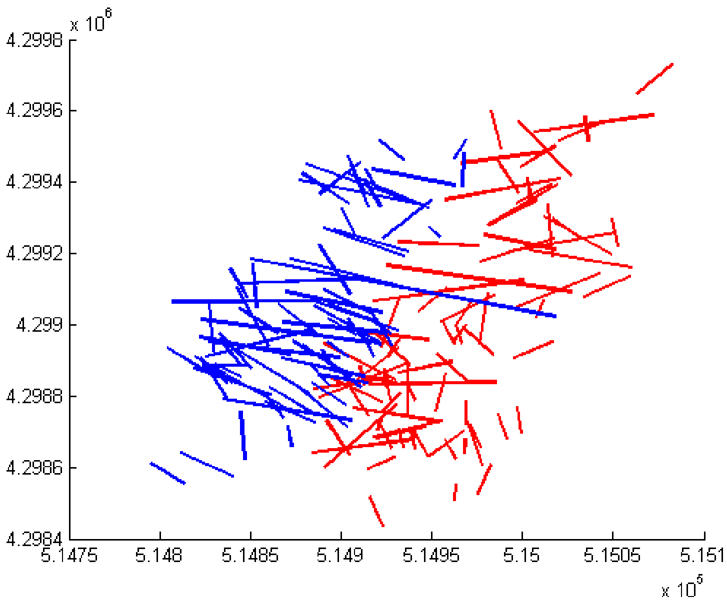

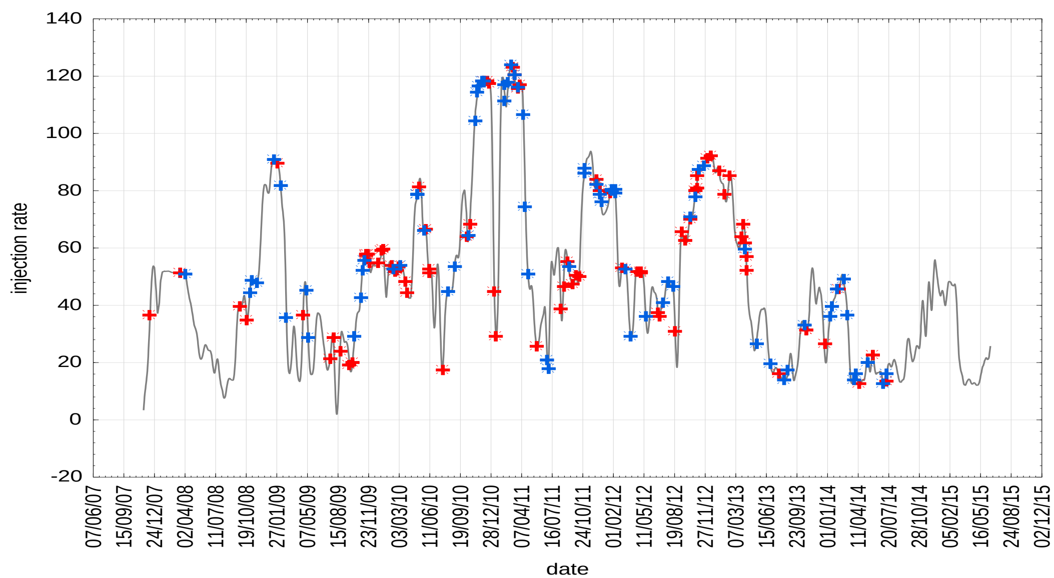

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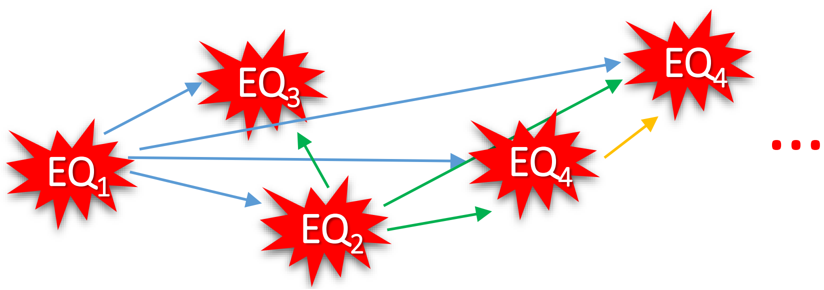

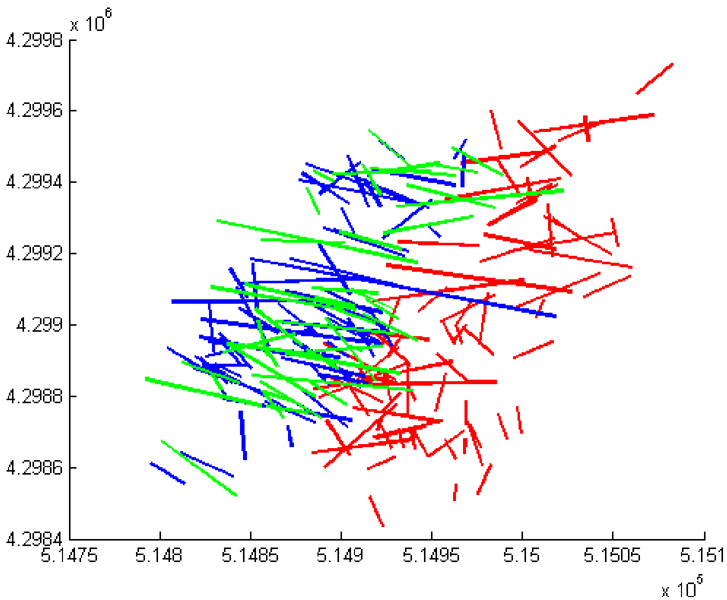

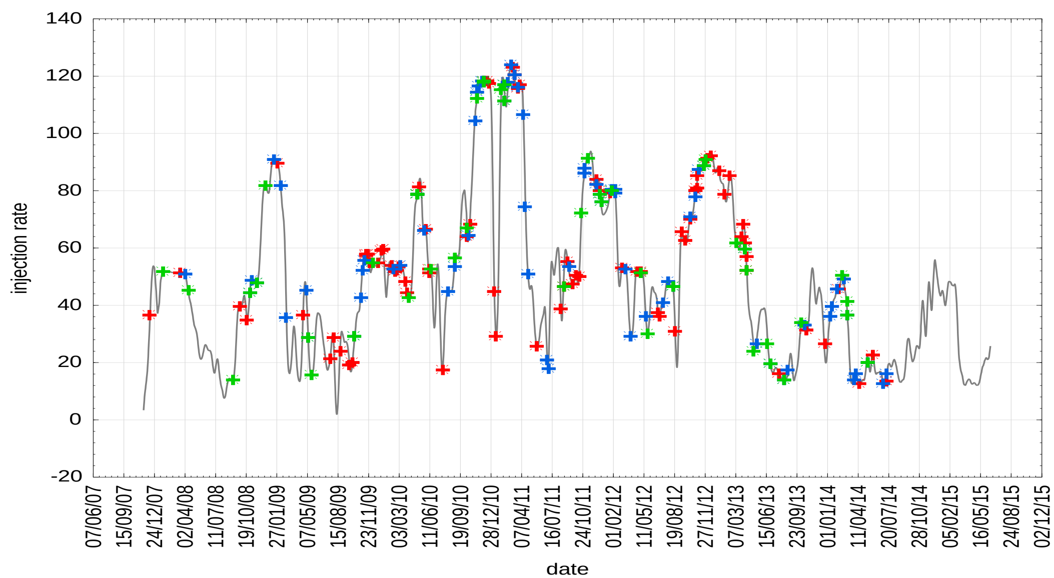

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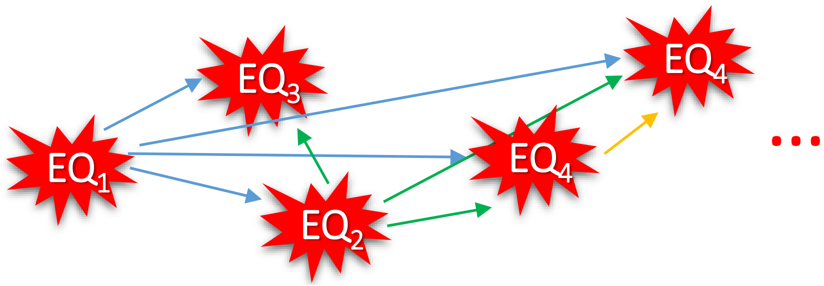

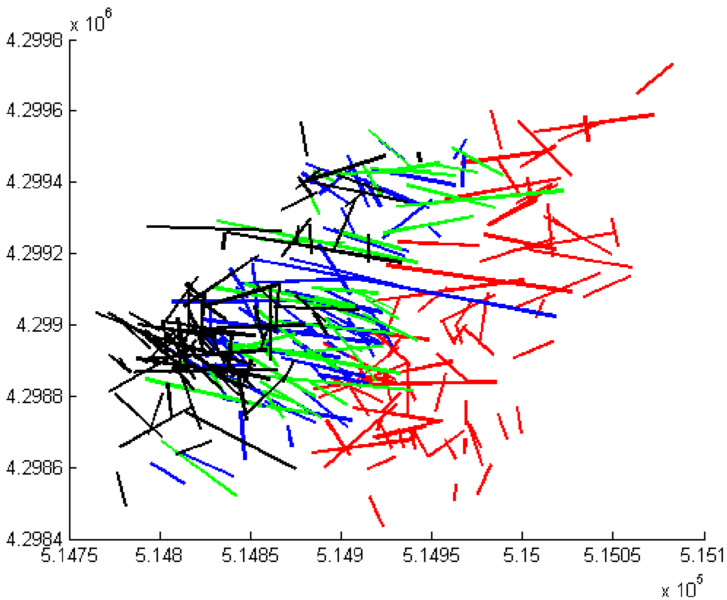

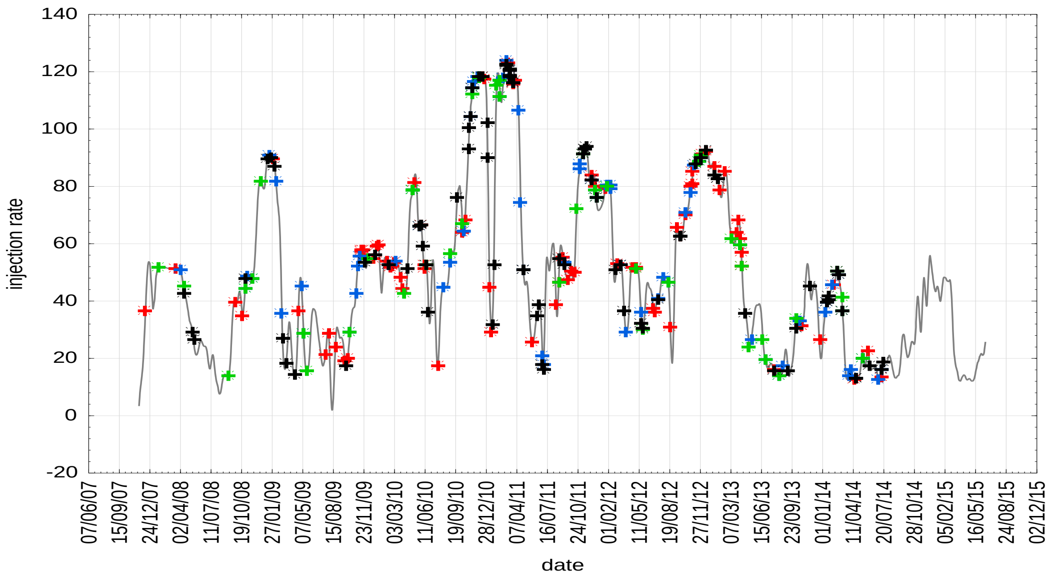

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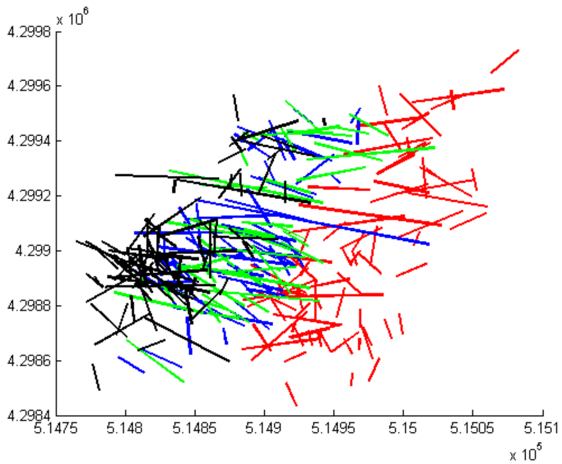

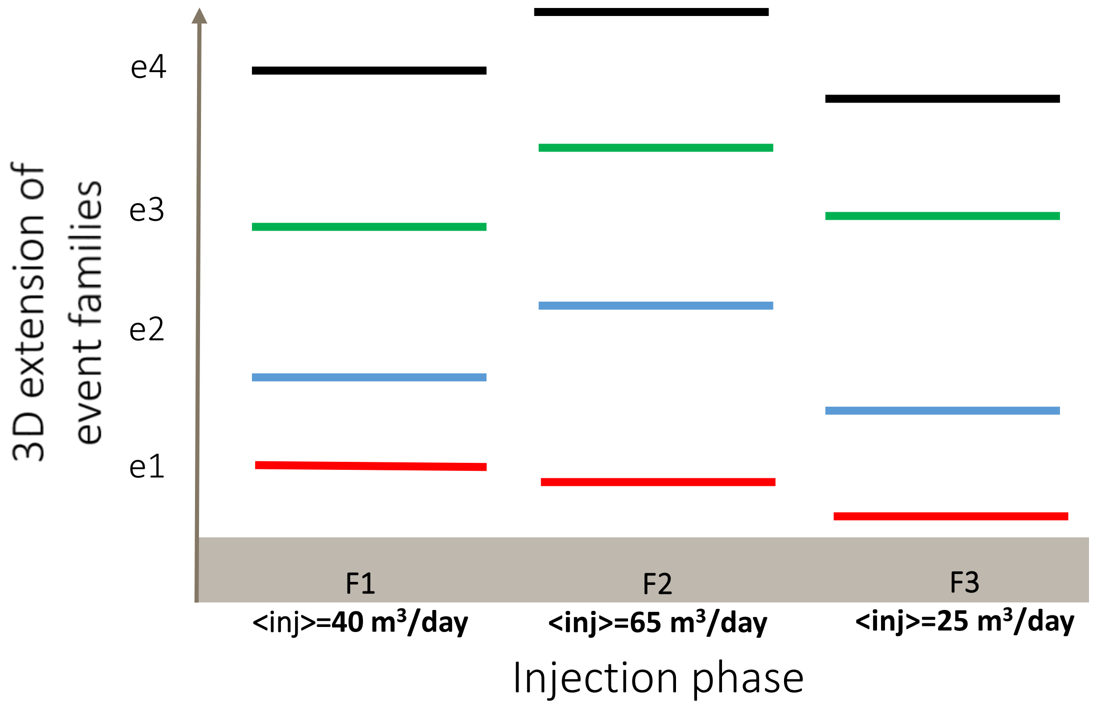

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Global approach. Disorder of seismicity is quantified by:

$$ZZ = \left\{ \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \sqrt{\Delta_r^2(i,k) + \Delta_M^2(i,k) + \Delta_\varphi^2(i,k)} \right\} \Big/ \frac{n(n-1)}{2}$$

$$\Delta_r(i,k) = \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2 + (z_i - z_k)^2}$$ - the distance between hypocentres of EQ-s „i”, „k”

$$\Delta_M(i,k) = \sqrt{(dip\_T_i - dip\_T_k)^2 + (strike\_T_i - strike\_T_k)^2 + (dip\_P_i - dip\_P_k)^2 + (strike\_P_i - strike\_P_k)^2}$$

- the total distance between axes T of EQ-s „i”, „k” and axes P of EQ-s „i”, „k”

$$\Delta_\varphi(i,k) = \sqrt{(\Theta_i - \Theta_k)^2 + (\varphi_i - \varphi_k)^2}$$ - the distance between radial vectors of EQ-s „i”, „k” in the local coordinate system with origin at Prati-9

n - the number of EQ-s

ZZ correlates strongly with the injection rate:

Correlation of ZZ with mean injection rate. The parameters were calculated in the sliding 50 event window, advanced by 10 events.

Injection Phase	Correlation coefficient	*p* - value
F1	0.43	0.0522
F2, total injection of Prati-9 and Prati-29	0.71	2×10^{-11}
F3	-0.72	0.0051
F1+F2+F3, total injection	0.39	5×10^{-5}

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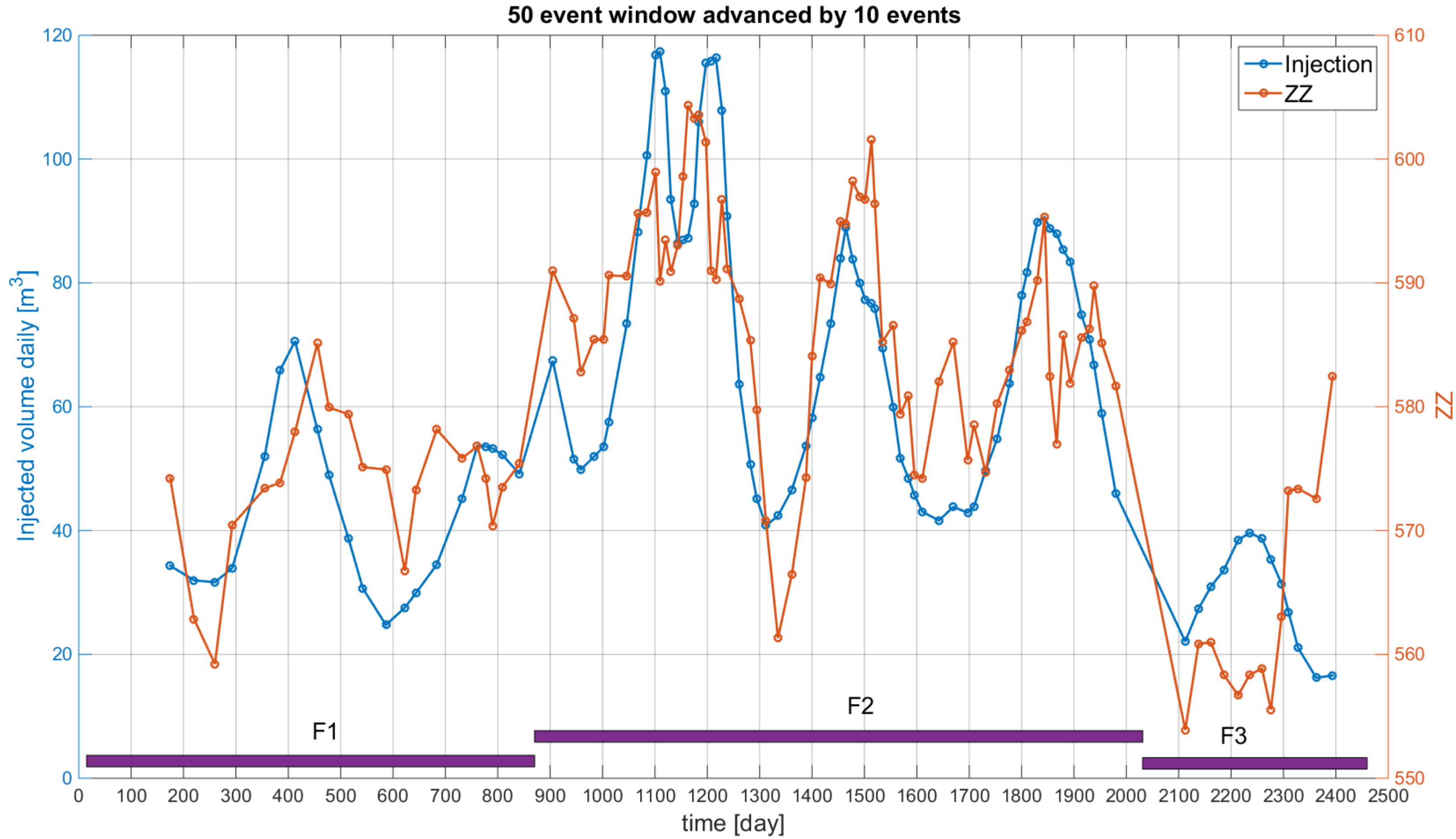

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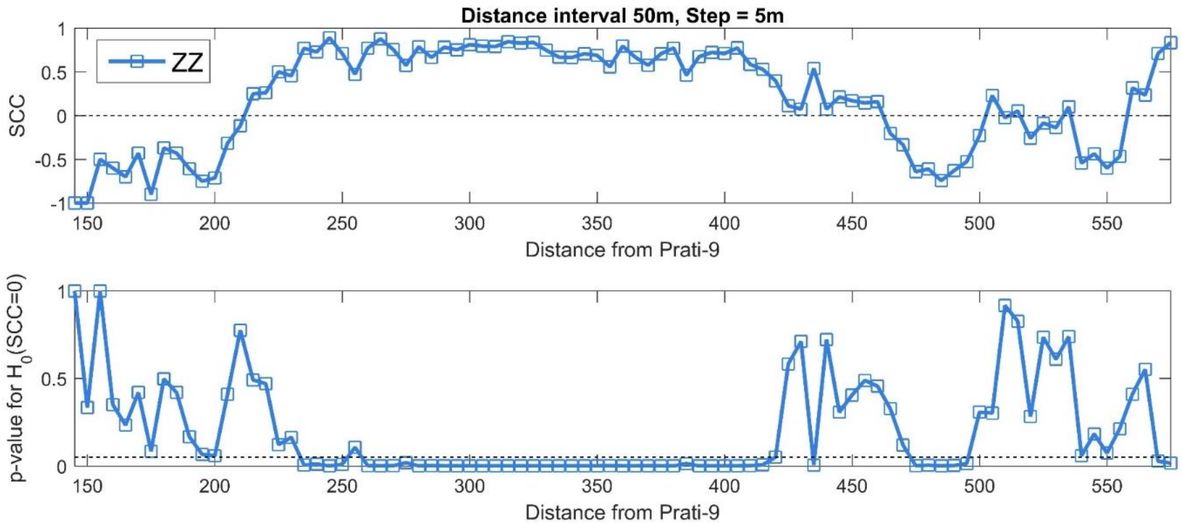
Correlation of ZZ with the injection rate versus hypocentral distance from the Prati-9 open hole:



No correlation	Positive	Negative	*(Unstable)*
R_{ZZ}=-0.01 (*p=0.96*)	R_{ZZ}=0.67 (*p=0*)	R_{ZZ}=-0.64 (*p=0*)	-0.50<R_{ZZ}<0.75
170 events	626 events	141 events	184 events

0m 250m 450m 500m 600m

Distance from Prati-9 injection well

Sperical shell volume	0.065 km^3	0.316 km^3	0.142 km^3	0.381 km^3

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Summary and Conclusions:

- The transformation to equivalent dimensions makes it possible to construct Euclidean metric spaces, based on the sets of quite different earthquake parameters.
- The total distance between the transformed deflection and rotation of earthquakes can be used to extract families of events, which located on similar directions and had similar focal mechanisms. The extension of such event families seems to correlate with the mean injection rate.
- The state variable *ZZ*, that is the sum of total distances between hypocenters, T and P axes and radial vectors of every two earthquakes, is used to quantify disorder of seismicity. *ZZ* correlates with mean injection rate in each of the three phases of injection, though delays of *ZZ* change with respect to injection rate change are observed for some times.
- In the first two phases the correlation is positive – the increased injection increases the disorder of seismicity. In the third phase the correlation is negative – the increased injection organizes seismic sources. It is possible that in this phase an elevated injection induces a mechanisms of linking the already existing fractures.

Thank you

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In general, the probabilistic models for earthquake parameters, F_{Xk}, are not known

→ Replacing F_{Xk}, $k = 1, \ldots, p$ with their data-driven, kernel estimators:

$$\hat{F}_X(x \mid \{x_i, n\}) = \frac{1}{n}\sum_{i=1}^{n}\Phi\left(\frac{x - x_i}{\lambda_i h}\right) \qquad \textit{with} \qquad \Phi(u) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{u} e^{-\frac{\xi^2}{2}}\, d\xi$$

***h*: common bandwith factor** *(estimated after Kijko et al., 2001)*
***λ*: local bandwidth factors:**

$$\lambda_i = \frac{1}{\left[\dfrac{\hat{f}^*(x_i \mid \{x_i, n\}}{g}\right]^{1/2}} \qquad \textit{with} \qquad g = \left[\prod_{i=1}^{n} \hat{f}^*(x_i \mid \{x_i, n\})\right]^{1/n}$$

and

$$\hat{f}^*(x_i \mid \{x_i, n\}) = \frac{1}{\sqrt{2\pi}\, hn}\sum_{i=1}^{n}\exp\left[-\frac{(x - x_i{}^2)}{2h^2}\right]$$