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Stochastic modelling of injection-induced seismicity in the Cooper Basin enhanced geothermal system

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I. Background

- Enhanced Geothermal Systems (EGS) are developed for the exploitation of geothermal heat energy from “hot” rocks at depths of several kilometres below surface.

- Even though EGS can theoretically provide an alternative and unlimited source of clean energy, a drawback emerges from induced microseismicity that in some case can reach larger magnitudes.

- A characteristic of injection-induced seismicity is its spatial migration with time, which is considered indicative of pore-pressure diffusion and the geometry of the stimulated volume in which permeability is enhanced.

- Understanding the details of earthquake migration during stimulation operations is particularly important for the design of EGS, the management of operations, as well as for the mitigation of hazardous induced earthquakes.

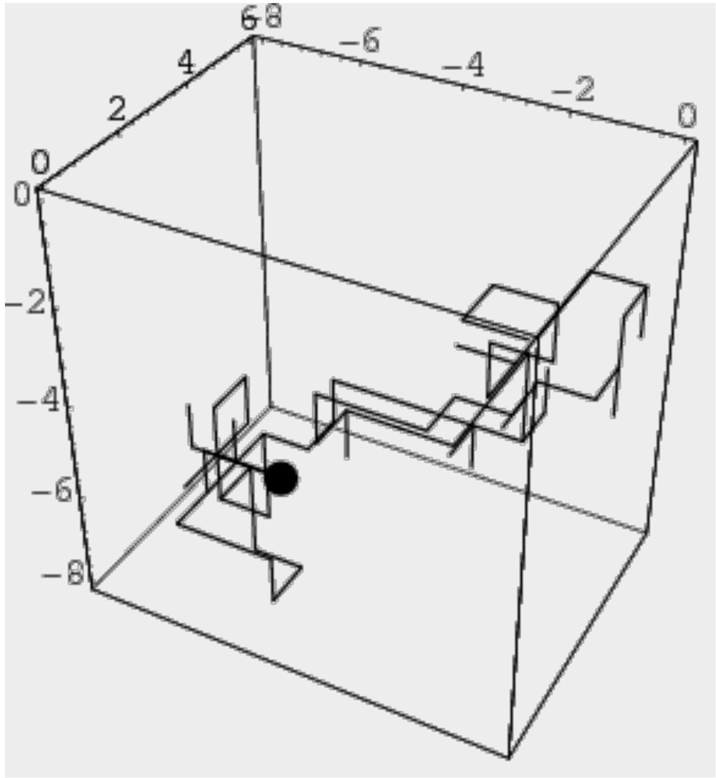
- Herein, we develop a nonlinear stochastic model (Michas & Vallianatos, 2018a), based on the Continuous Time Random Walk (CTRW) theory, to map the spatiotemporal evolution of injection-induced seismicity.

- We further apply the model to two stimulation experiments in the Cooper Basin EGS (SE Australia).

II. Stochastic model

- The Continuous Time Random Walk (CTRW) theory is well-established for modelling nonlinear fluid transport in complex heterogeneous media (e.g., Berkowitz et al., 2006).

- The CTRW model considers a random walker, who starting from the origin (x_0=0) at time t_0=0 and staying fixed to this position until time t_1, he makes a jump of length r_1 to the position x_1. He then stays at this position until time t_2, when he jumps to a new location x_2 of length r_2 from the previous one and the process is renewed (Figure).



- Within this context, waiting times and jump lengths between the successive earthquakes are considered as continuous random variables drawn from a joint probability density function $\psi(x, t)$.

- Finite characteristic waiting times T and jump length variances σ^2 correspond to *normal diffusion* (Brownian motion), while for divergent T and σ^2 *anomalous diffusion* arises (e.g., Bouchaud & George, 1990).

II. Stochastic model

- In normal (Brownian) diffusion the mean squared displacement (msd) grows linearly with time:

$$\left\langle x^2(t) \right\rangle \sim Dt$$

- Instead, the hallmark of anomalous diffusion is the non-linear growth of the mean squared displacement (msd) with time that frequently takes the form of a power-law function:

$$\left\langle x^2(t) \right\rangle \sim t^a$$

x – the distance of the propagator from the initial point, t – the time.

- The exponent α characterizes the different domains of anomalous diffusion (e.g., Metzler & Klafter, 2000). For $\alpha >$ 1 the transport is super-diffusive. For $0 < \alpha < 1$, subdiffusive and for $a = 1$ normal diffusion is recovered.

II. Stochastic model

- The objective of using the CTRW theory is to estimate the probability $p(x,t)$ of an earthquake to occur at some position x after time t.

- In the case of normal diffusion, $p(x,t)$ is governed by the linear (Fickian) diffusion equation:

$$\frac{\partial p}{\partial t} = D \frac{\partial^2}{\partial x^2} p(x,t)$$

- In the anomalous diffusion regime, the *fractional diffusion equation* (FDE) can instead be used to model the propagation of the walker $p(x,t)$.

$$\frac{\partial p}{\partial t} = {}_0D_t^{1-\alpha} K_\alpha \frac{\partial^2}{\partial x^2} p(x,t)$$

In the FDE, K_a is the generalized diffusion constant and ${}_0D_t^{1-a}$ the Riemann-Liouville operator.

II. Stochastic model

- The probability distribution $F(x, t)$ of an earthquake having just occurred at position x at time t can be obtained from the FDE using the fractional Riemann-Liouville derivation. The asymptotic behavior of $F(x, t)$ in the subdiffusive regime, for large x and for arbitrary dimension d is given by (Helmstetter & Sornette, 2002):

$$F(x,t) \sim \frac{(\tau')^{-a}}{\sqrt{K_a} t^{1-(a/2)}} \left(\frac{|x|}{\sqrt{K_a t^a}} \right)^{d(1-a)/(2-a)} \times \exp\left[-\left(1-\frac{a}{2}\right)\left(\frac{a}{2}\right)^{a/(2-a)} \left(\frac{|x|}{\sqrt{K_a t^a}} \right)^{2/(2-a)} \right]$$

a: the power-law exponent of the mean squared displacement (msd)

d: the dimension

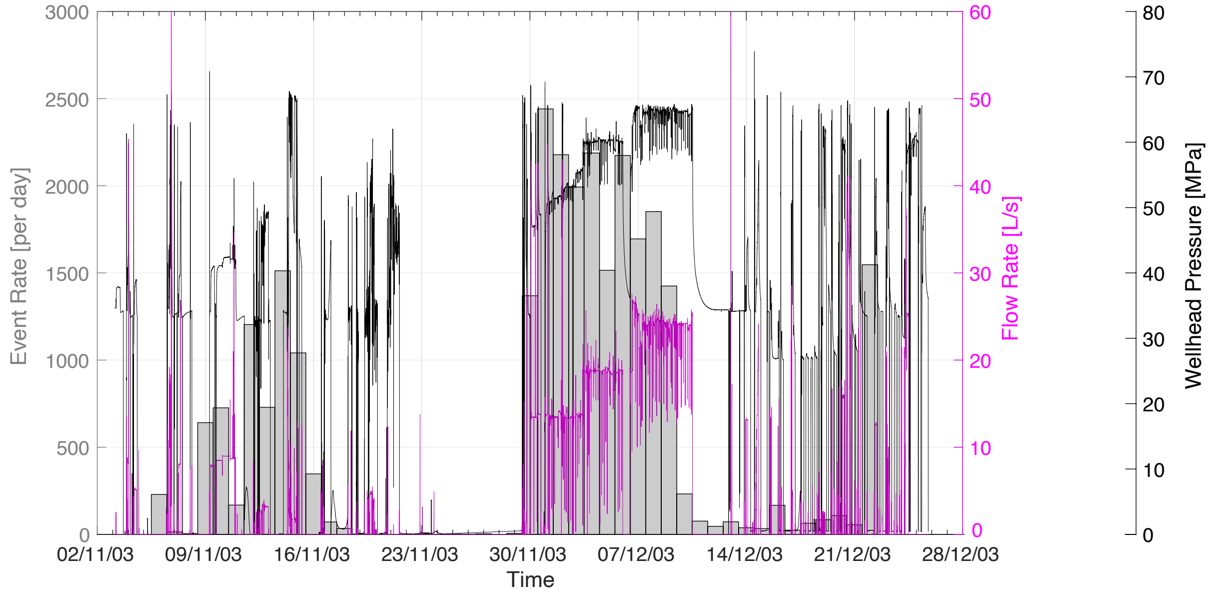
$\tau' = T\left(\Gamma(1-a)\right)^{1/a}$, where T is the characteristic waiting time $T = \int_0^{\infty} dt p(t) t$

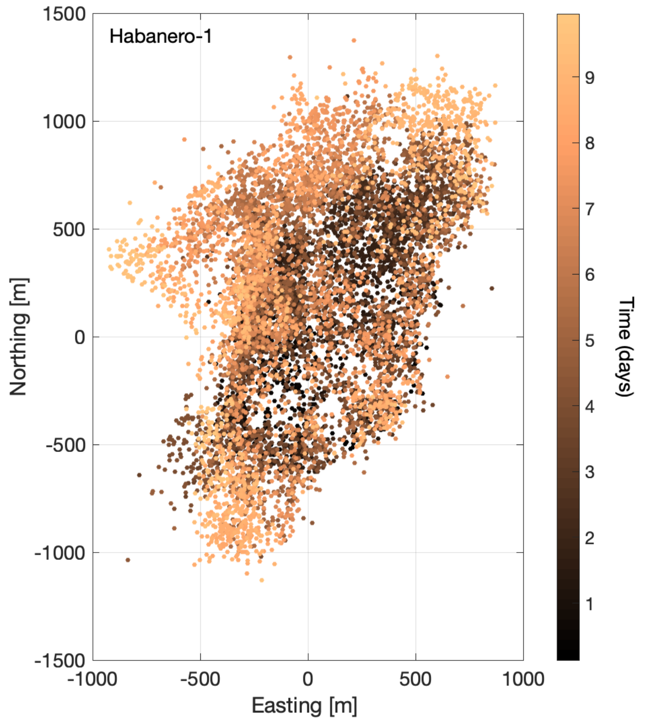
$K_a \equiv \sigma^2 / T^a$, where σ^2 is the jump length variance $\sigma^2 = \int_{-\infty}^{+\infty} dx \lambda(x) x^2$

III. Application to the Cooper Basin geothermal field

- The Cooper Basin geothermal field is located in the northeast of South Australia. Starting in 2002, several hydraulic stimulations were conducted to enhance permeability in the subsurface.

- In 2003, more than 20,000 m^3 of water were injected at high pressures into the well Habanero #1 (Figure to the right).

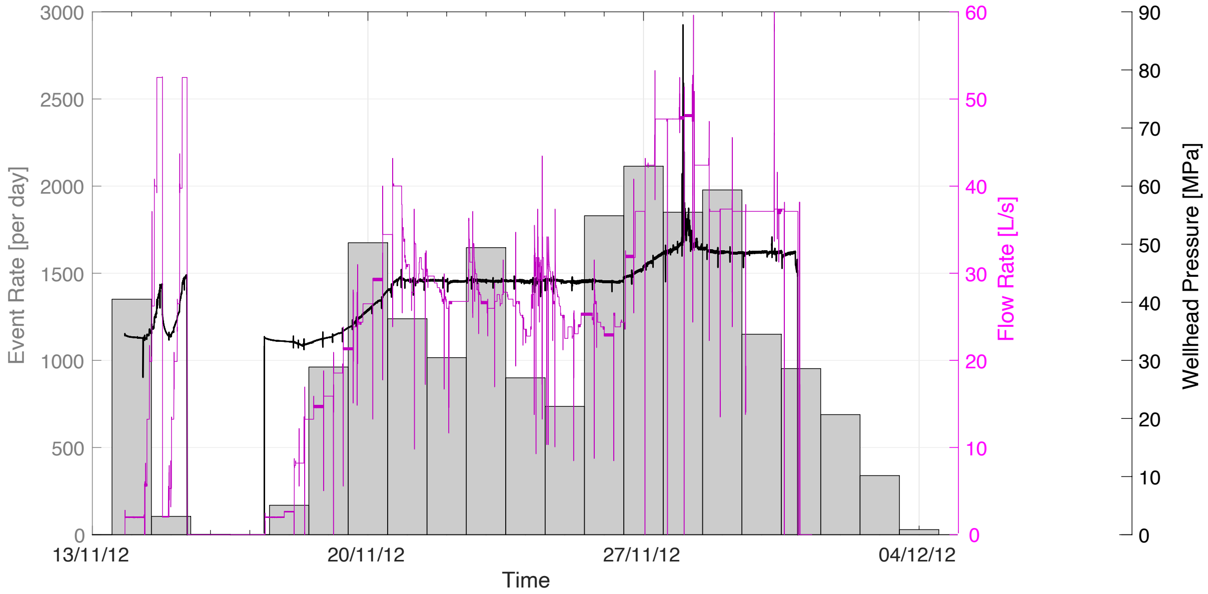




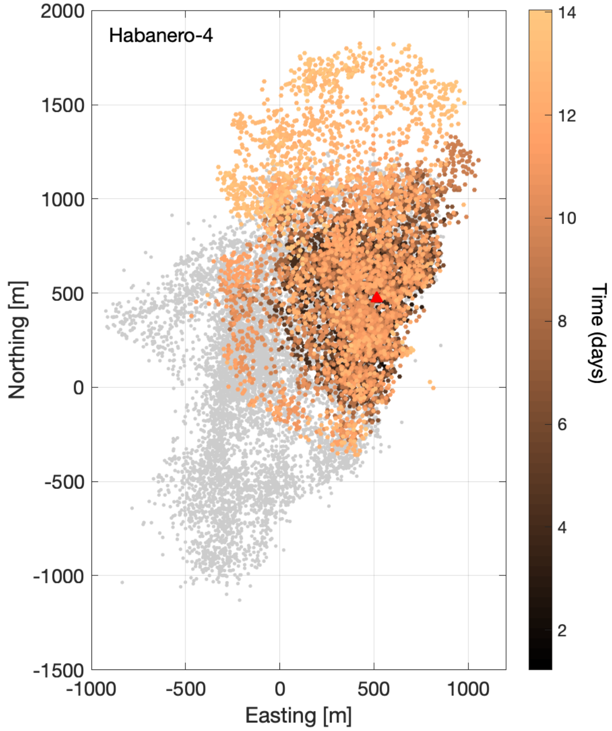
- During the main stimulation phase (30/11 – 09/12/03) more than 15,500 induced earthquakes were recorded (Figure to the left).

III. Application to the Cooper Basin geothermal field

- Following previous stimulations, in 2012 approximately 34,000 m^3 of water were injected in the well Habanero #4 (Figure to the right).



- During the main stimulation period (18/11 – 04/12/12) more than 19,000 induced earthquakes were recorded and located (Figure to the left).



- Hypocenter locations indicate a single subhorizontal fracture zone at ~4160 m depth (Baisch et al., 2015).

- Epicenter distribution indicates the systematic migration of seismicity away from the well with time for both stimulation experiments.

III. Application to the Cooper Basin geothermal field

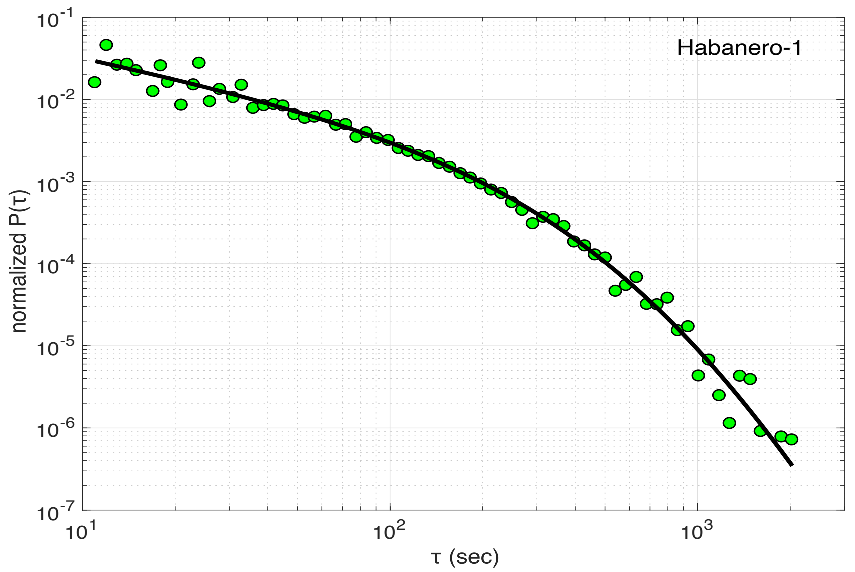
- The probability density $P(\tau)$ of waiting times τ between the successive earthquakes during the two hydraulic stimulations is constructed.

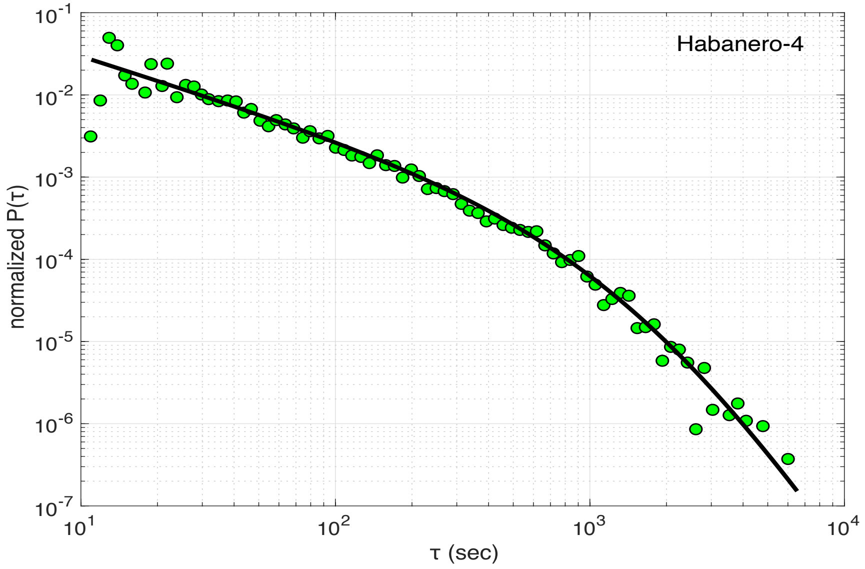
- $P(\tau)$ presents bimodal behavior. For short τ, $P(\tau)$ decays slowly up to a characteristic waiting time where a gradual crossover to faster decaying probabilities appears for larger τ (Figures).

- This scaling behavior is approximated with the q-generalized gamma function (Michas and Vallianatos, 2018b):

$$f(\tau) = C\left(\frac{\tau}{\tau_0}\right)^{\gamma-1} \exp_q\left(-\frac{\tau}{\tau_0}\right) \quad \text{, where} \quad \exp_q(x) = \left[1+(1-q)x\right]^{1/(1-q)}$$

- $P(\tau)$ for both Habanero-1 and -4 can well be approximated with the q-generalized gamma function (Figures), indicating clustering effects at both short- and long-time scales.



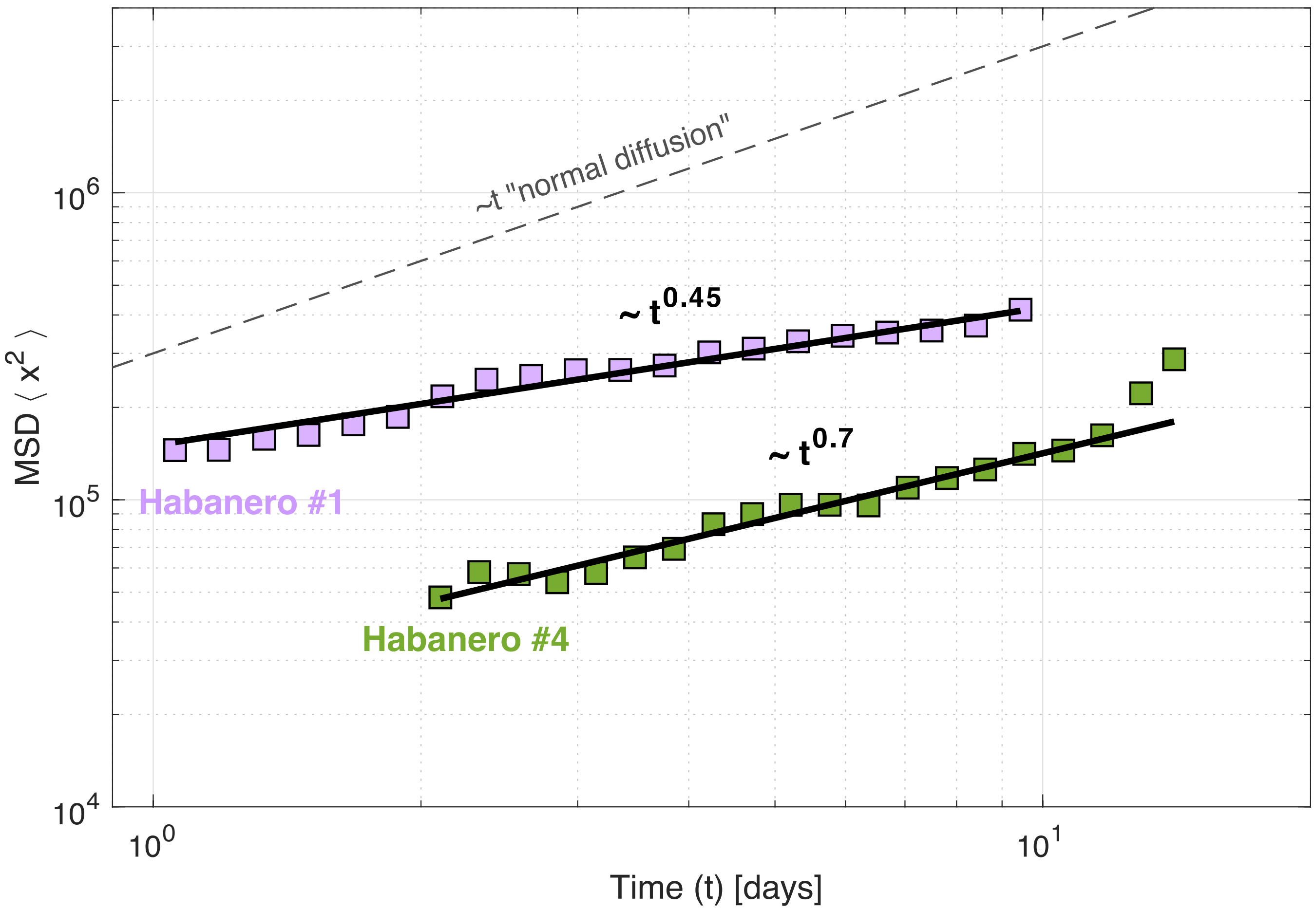


III. Application to the Cooper Basin geothermal field

- ❖ The msd of induced seismicity with time for Habanero-1 and -4 is constructed (Figure), taking as the origin of the random walk the wells' cashing shoes.

- ➢ The msd grows almost continuously with time and approximately as a power-law, with exponents *a*=0.45 ±0.04 for Habanero-1 and *a*=0.7 ±0.05 for Habanero-4 (Figure).

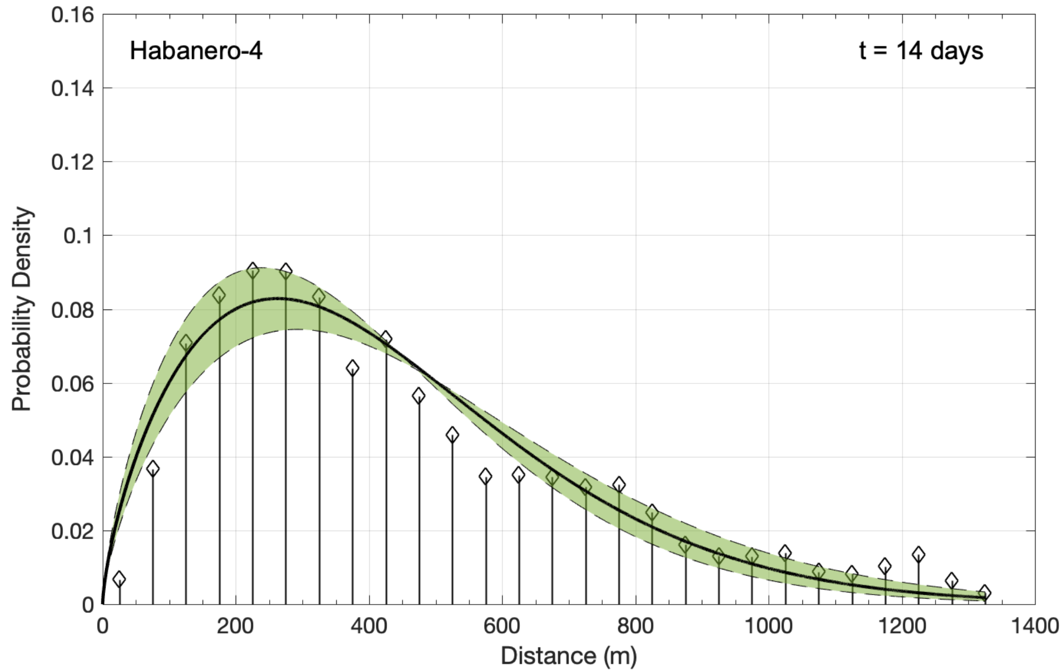
- ➢ The lower than unity exponents *a* indicate *anomalous diffusion* of induced seismicity according to a slow *subdiffusive* process.

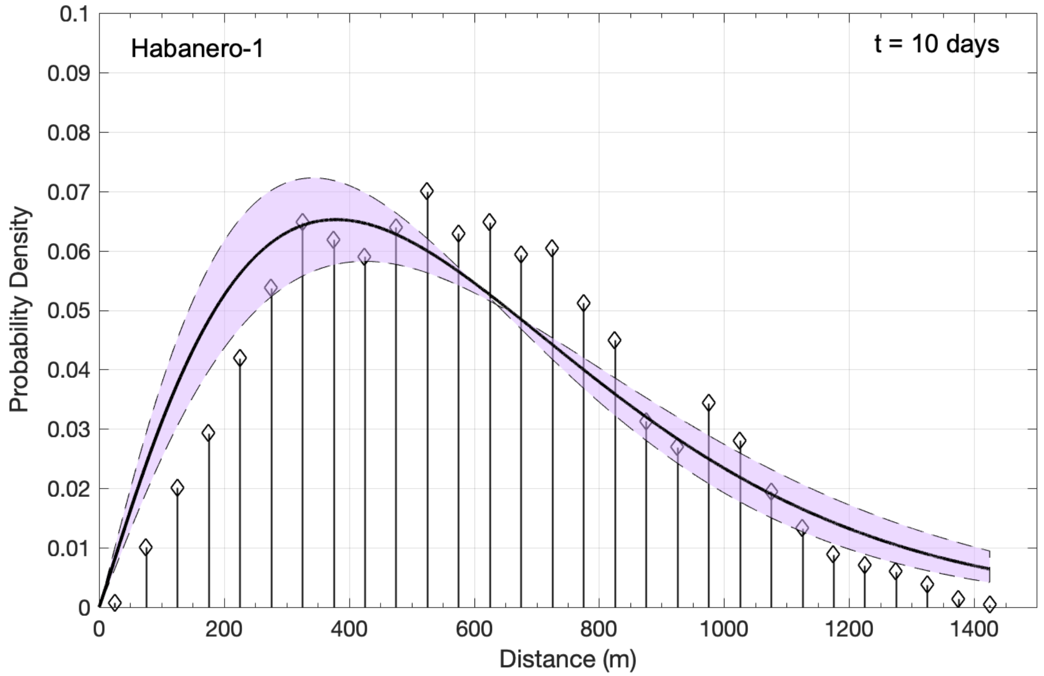


III. Application to the Cooper Basin geothermal field

- The propagation of induced seismicity in space and time is examined in terms of the pdf $F(x,t)$, the histogram of the absolute 3D distances between each induced event and the origin (Figures).

- We use the asymptotic solution of the fractional diffusion equation (FDE) to model $F(x,t)$.

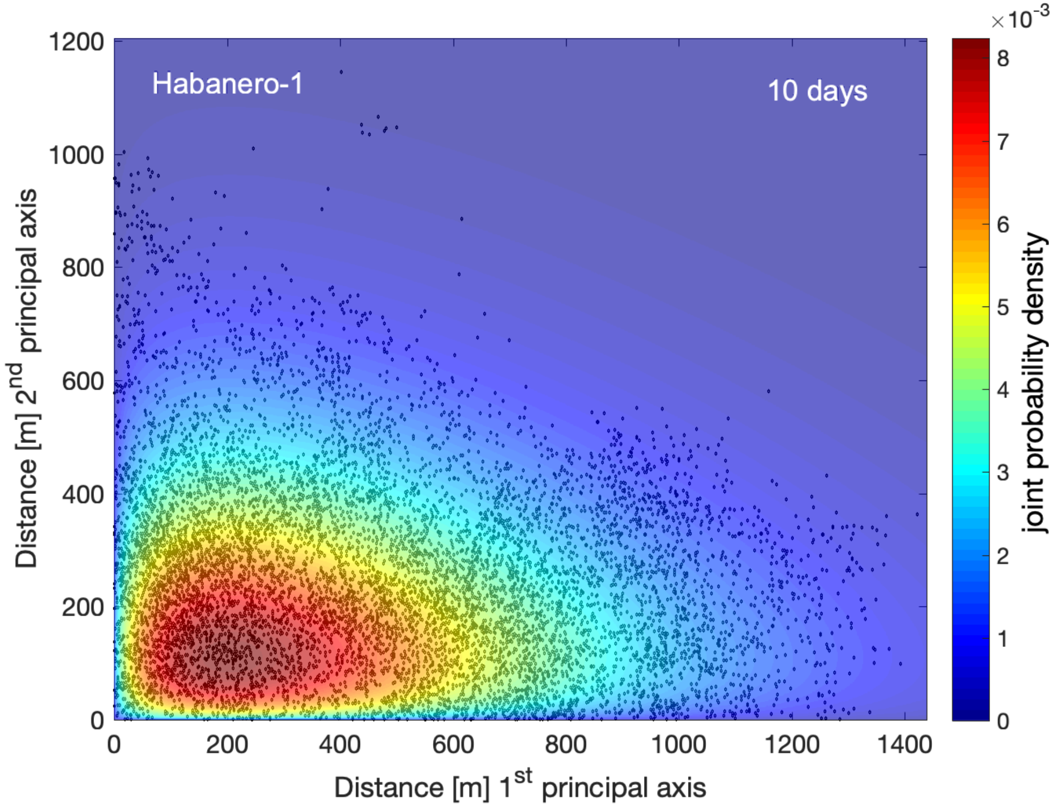


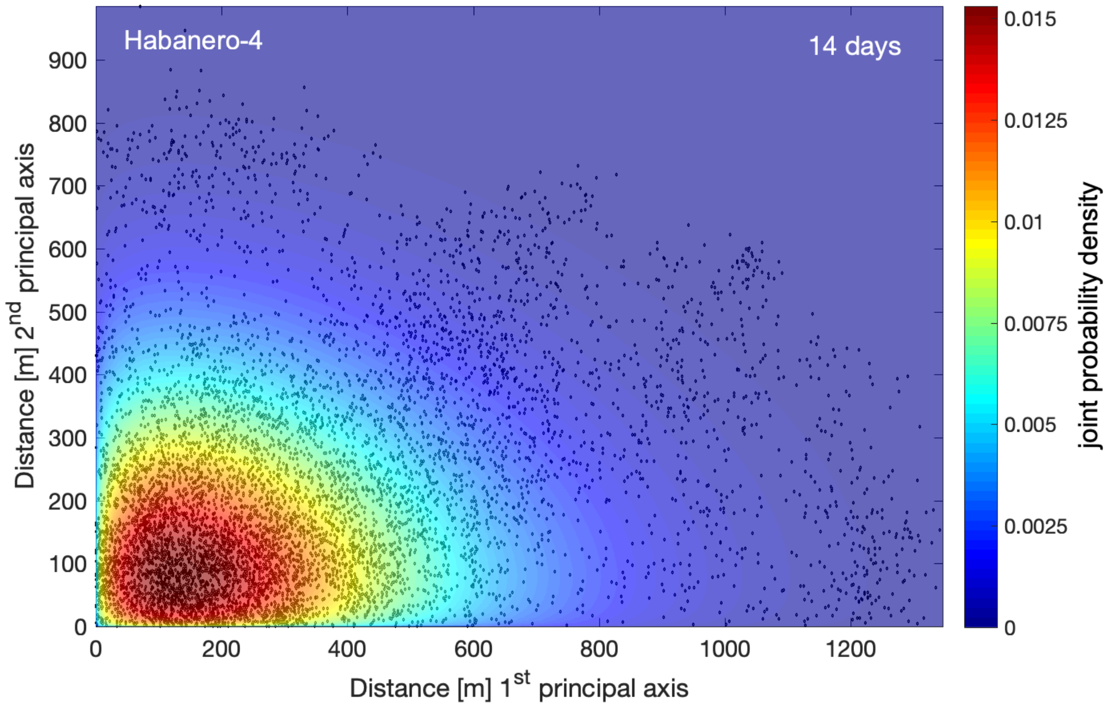


- The model successfully captures the main features of earthquake occurrence (Figures), regarding the peak of concentration close to the injection-site and the stretched relaxation of seismicity with distance.

III. Application to the Cooper Basin geothermal field

❖ Figures show the propagation of induced seismicity in the 2D space, along the principal axes of an ellipse that best fits the seismicity cloud and the prediction of the FDE model (colorbar).





➢ The model successfully predicts the area of greater earthquake occurrence close to the origin, the greater extend of seismicity along the first principal axis and the decay of earthquake occurrence with distance.

IV. Conclusions

- The analysis and results demonstrate the complex propagation and the *anomalous* (non-Fickian) *diffusion* of injection-induced seismicity in the Cooper Basin EGS, a process that might be expected in most cases of fluid-induced seismicity in the highly heterogeneous and multi-fractured crust.

- The waiting times distributions indicate *clustering effects at all time scales* in the evolution of injection-induced seismicity in the Cooper Basin EGS, which contradicts the Poissonian assumption, where earthquakes occur randomly in time.

- The propagation of injection-induced seismicity in the Cooper Basin EGS corresponds to a slow *subdifussive* process, in accordance with the subdiffusion of regional seismicity (Huc & Main, 2003; Helmstetter et al., 2003; Michas & Vallianatos, 2018a; Michas & Vallianatos, 2020).

- In the case of the Cooper Basin EGS, the CTRW model can successfully be used to predict the main features of anomalous earthquake diffusion and the progression of induced seismicity in time and space.

Acknowledgements

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