Prediction of Induced Seismicity: a Machine Learning approach

Arthur Cuvier[1], Julie Maury[1], Hideo Aochi[1] and Hugo Breuillard[1]

[1]BRGM, F-45060 Orléans, France.

contact: a.cuvier@brgm.fr

It is well known that earthquakes can be induced by the injection of fluids into the ground. In this work, we investigate the correlation between induced seismicity and fluid injection parameters (flow rate, pressure, ...). We use a machine learning approach, particularly well suited to processing large volumes of data and extracting the complex link between injection parameters and seismicity. By training our model on time series characterising injection parameters and seismicity, we estimate the number of earthquakes occurring in the future. We propose to focus on two case studies having caused induced seismicity at different spatial and temporal scales. Firstly, we estimate the future number of induced earthquakes in central Oklahoma (U.S), which has been subject to extensive waste water disposal since 2010. Data analysis shows a clear correlation between seismicity rate and injected volums with a 9 months delay. Secondly, we focus on the seismicity during the stimulation phase of the Soultz-Sous-Forêts (France) enhanced geothermal system (EGS) in 2005. Taking advantage of injection flow rate and wellhead pressure time series, we predict the seismicity over the next 24 hours. Finally, this work paves the way for another future application: real-time prediction of induced seismicity during continuous fluid injection.

A - Wastewater injection in Oklahoma (U.S)

Since 2010, large volumes of wastewater have been injected in the ground in central Oklahoma, causing a sharp increase of the observed seismicity.

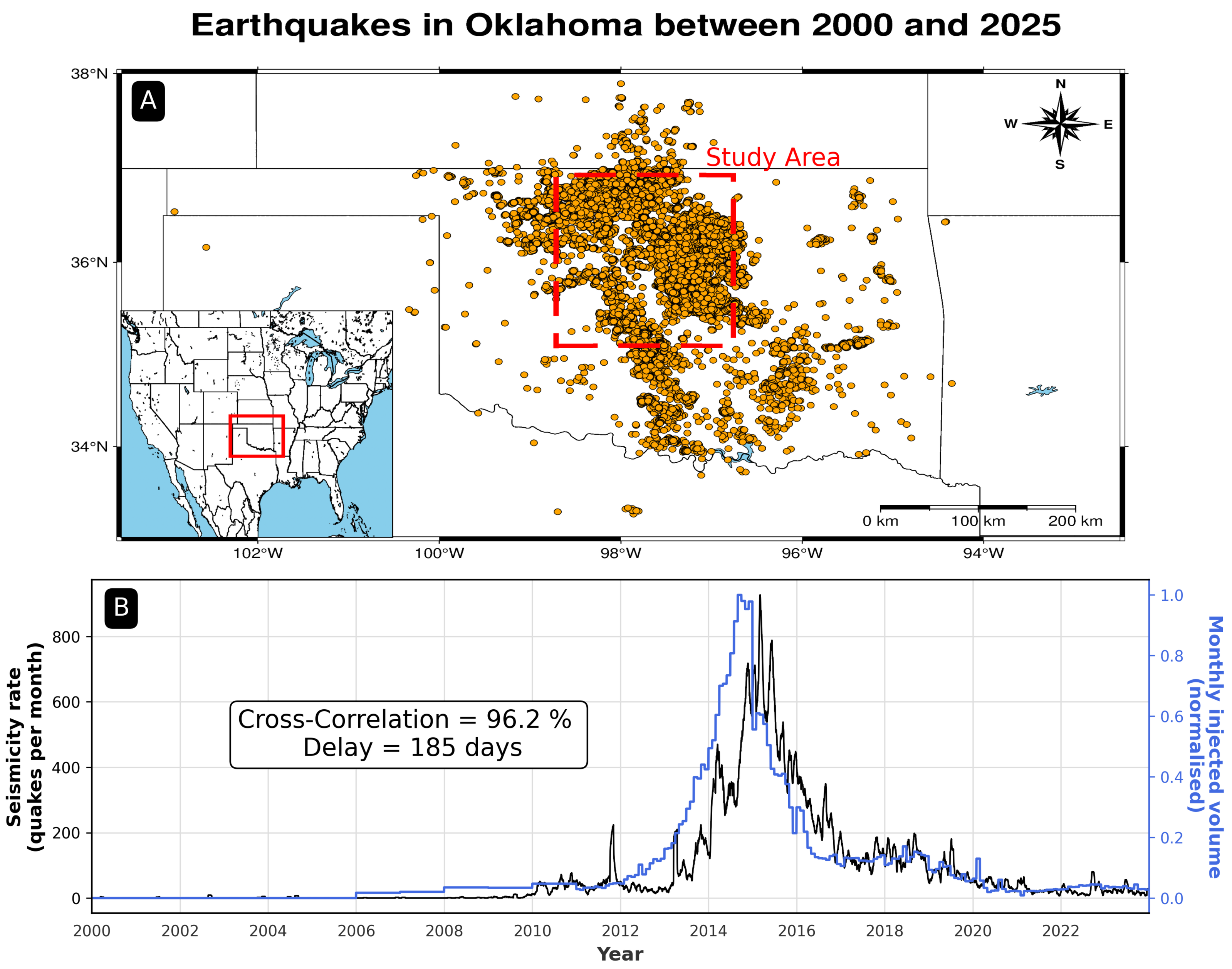

Fig. 1: (A): Seismicity in Oklahoma between 2000 and 2025 ($M_W \geq 1.8$) (B): Correlation between seismicity and injected volume in the study area.

As a clear correlation is observed, we use a **linear regression** approach to capture the relationship between **injected volume** and **seismicity rate**.

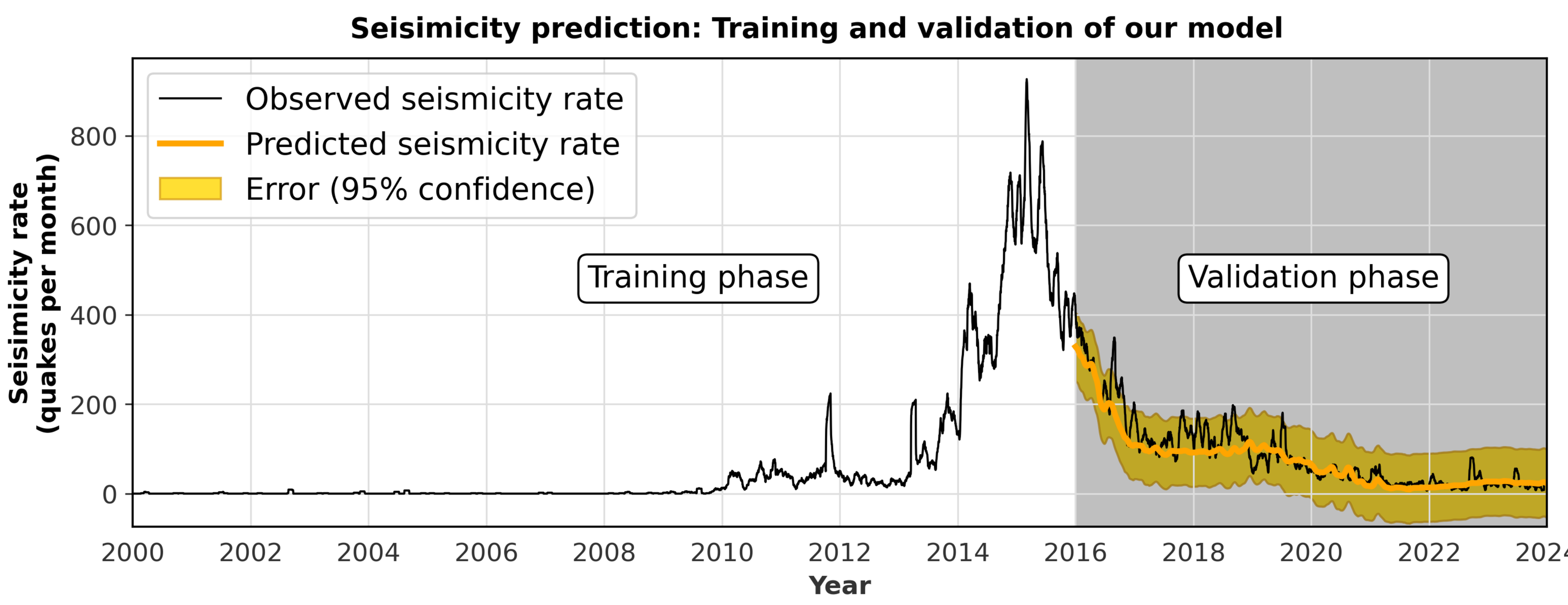

Fig. 2: Seismicity rate: Observation VS Prediction.

Our model offers better predictions than the one proposed by [1] and does not require complex modelisation of the underground pressure.

Since our trained model provides accurate estimations during the validation phase (mean error of 22.2 quakes/month), we use it to predict the future seismicity rate of two hypothetical injection scenarios up to 2027.

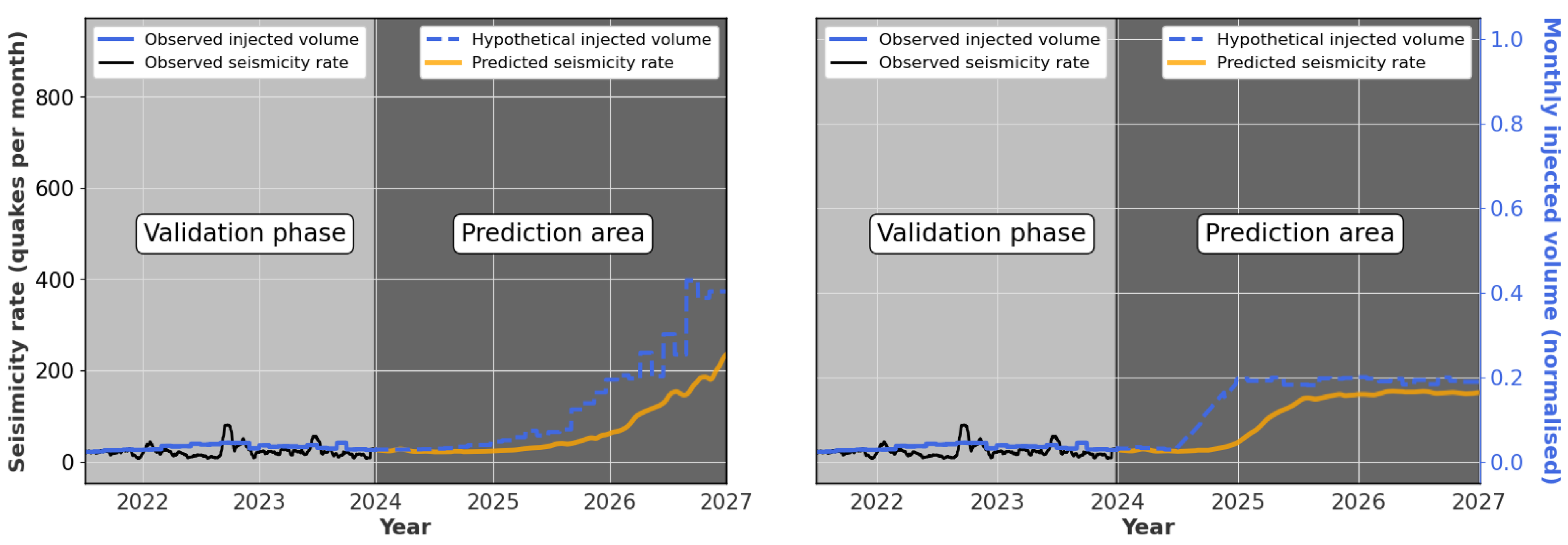

Fig. 3: Three years seismicity prediction for two injection scenarios.

Any injection scenario may be tested to predict the associated seismicity.

Reference: [1] Qin, Yan, et al. (2022).

B - EGS hydraulic stimulation (Soultz-Sous-Forêts, France)

- The Soultz-Sous-Forêt enhanced geothermal system has undergone several phases of hydraulic stimulations during the last decades.
- These caused significant increases in local seismicity as shown in Fig 4 for the stimulation in 2005.

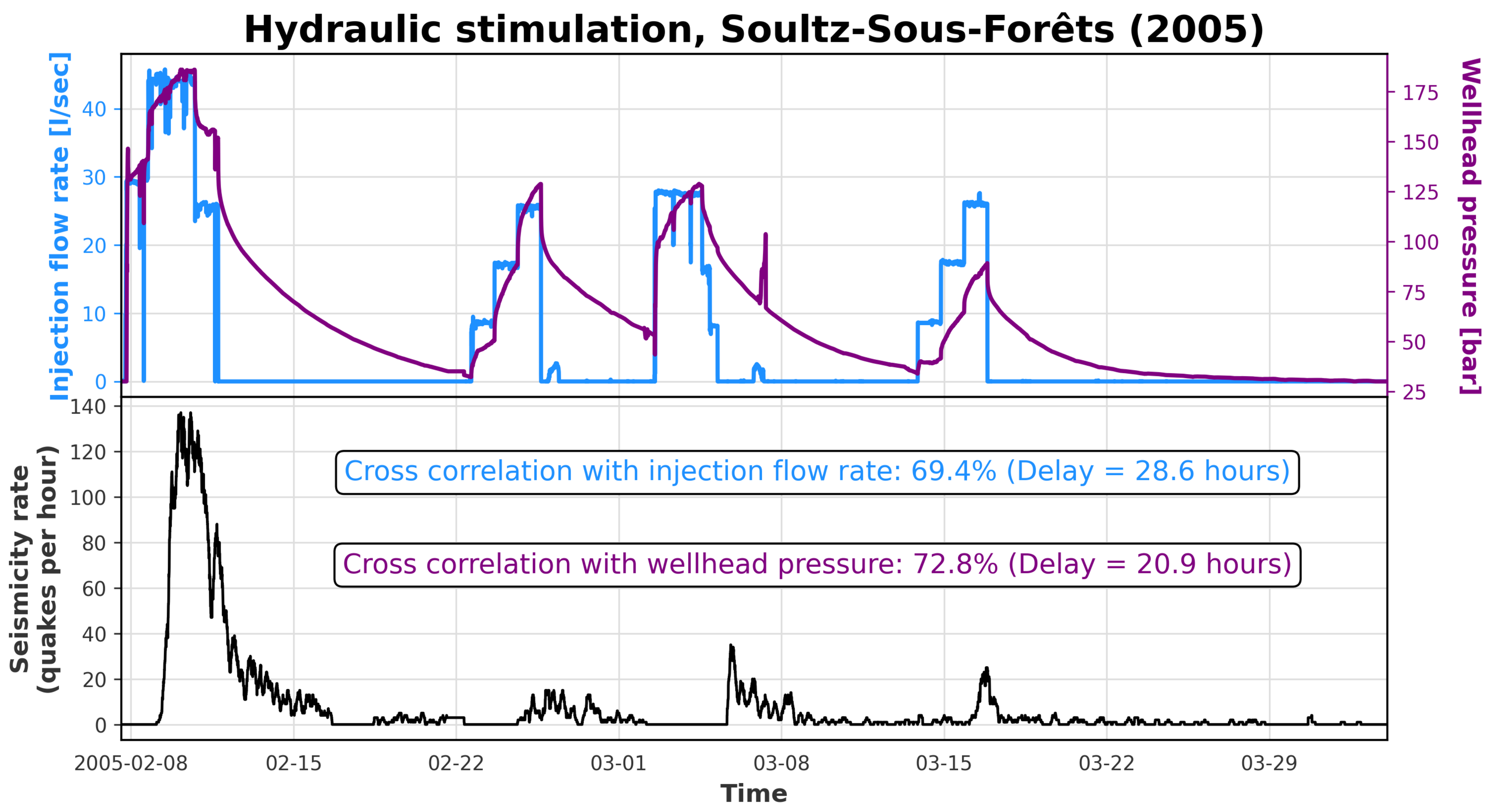

Fig. 4: Delayed correlation between injection parameters (top) and the seismicity rate (bottom).

As the relation between injection parameters and seismicity rate is more complex than the one observed in Oklahoma (*i.e.* non linear), we use a **Light Gradient Boosting Method (LGBM)** to perform the prediction.

The **LGBM** builds a model by combining regression trees in a sequential manner, where each new model corrects the errors of the previous one.

Our model predicts future seismicity for the next 24 hours, using **wellhead pressure** and **injection flow rate** data from the last 48 hours.

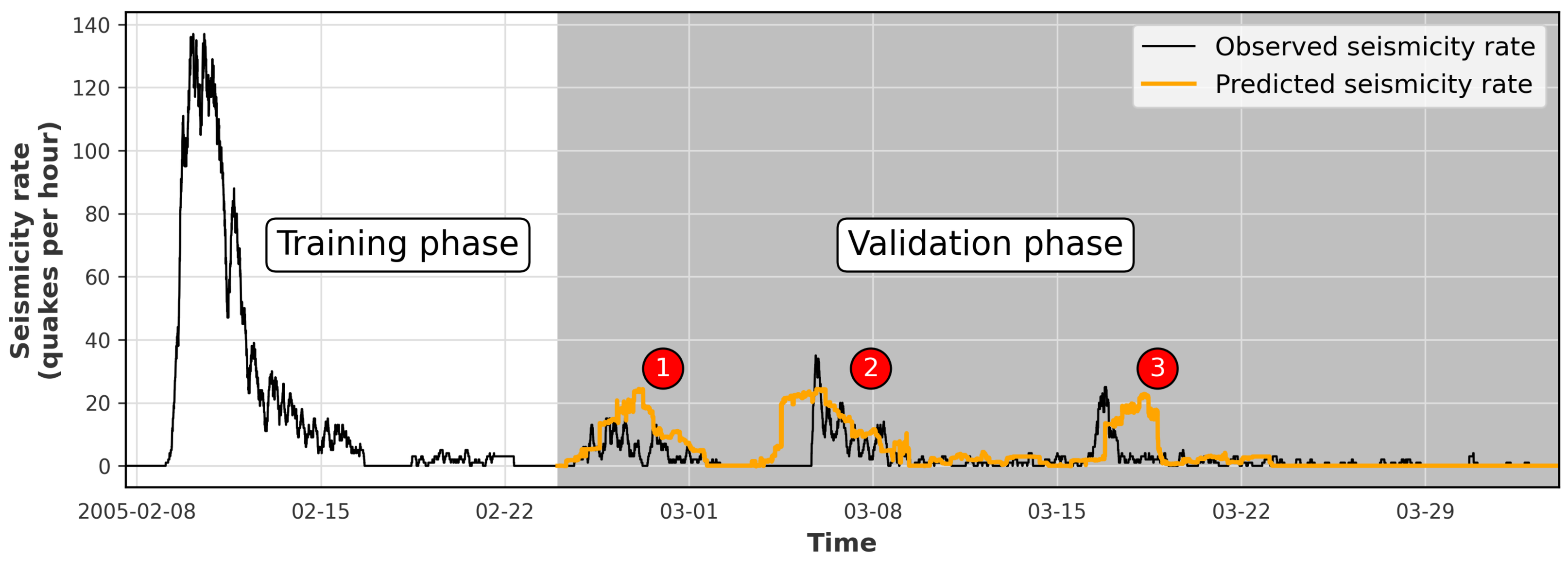

Fig. 5: Prediction of seismicity caused by the stimulation phase.

Using a relatively small proportion of data to train our model (around two weeks), we can predict the seismicity rate for the rest of the stimulation.

These predictions accurately estimate future seismicity trends, especially the three seismic crisis during validation phase (1, 2 and 3 in Fig 5) although slight time shifts are observed (work in progress).

Conclusion and perspectives

- Time series prediction is a powerful tool to quantify the future seismicity induced by fluid injection in the ground.
- The delay between injection parameters and seismicity proves to be a decisive characteristic in this approach.
- Finally, we aim to generalise this approach to other hydraulic stimulations, for which no delays have been observed.

This project is funded by ANR-22-FAI2-0008