Threats in flooded areas of coal mines in Europe: Focus on post-mining seismicity

INERIS
maîtriser le risque pour un développement durable

Authors: I. Contrucci, E. Klein, M. Al Heib
Institution: Ineris
Country: France

GFZ Helmholtz Centre Potsdam | Technische Hochschule Georg Agricola | GIG Research Institute | ÚGN Ústav geoniky – AV ČR | brgm Géosciences pour une Terre durable

Introduction

Following the **Paris Agreement**, adopted in 2015:

→ Europe has committed to **reduce its greenhouse gas emissions**
→ Several countries have decided **to gradually closing their coal mines**

→ Thus, the number of **closed mines will increase** in the years to come
  → Poland aims to close them by 2050
  → Germany by 2030
  → France have already closed all coal mining

→ **Management of potential residual risk** associated with these **thousands** of closed mines is a **crucial issue** in the years to come

Closure of mines & post-mining seismicity

National regulations related to the **closure of mines already exist** in **European** countries to manage the residual risks and the resulting nuisances for the population and the environment.

These regulations cover the issues of :

- the **stability of the overlying lands** (mining subsidence, uplift, and/or local collapses),
- the management of **the rise and the quality of the groundwater,**
- the **upwelling of gas,**
- the **rehabilitation of sites** after the cessation of mining works,

To date, the **characterization and management of the post-mining seismicity hazard are poorly or not at all taken into account** in public policies.

While it has been established since the late 1800's that active mining induces earthquakes, **the cases of post-mining seismicity remain insufficiently studied**

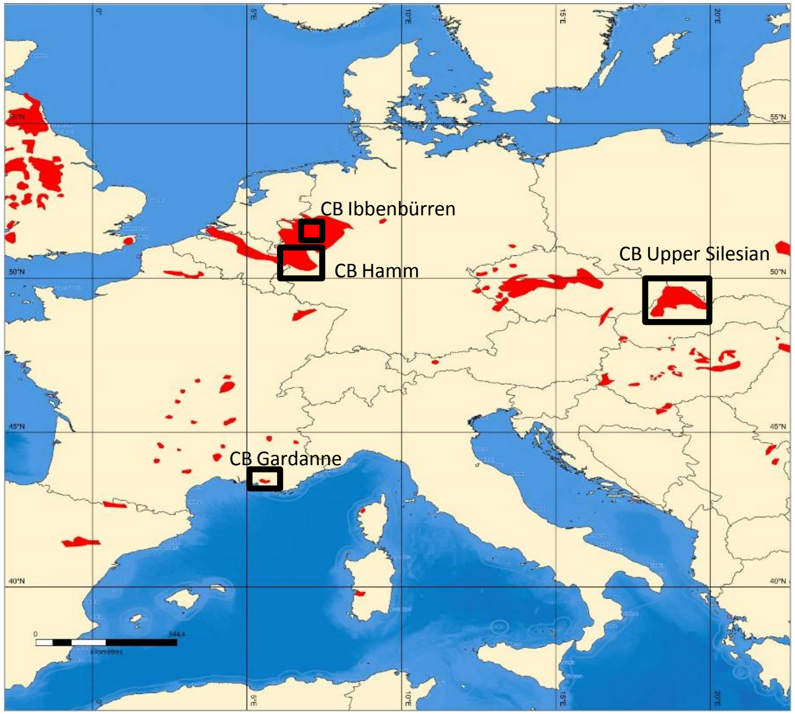
Example of Post-mining seismicity

A well-known case of post-mining seismicity occurred in **South Africa** with a **magnitude 5.3 earthquake on March 9, 2005** [Durrheim et al. 2007].

- It happened **several years** after the closure of the mine
- during its **flooding**
- caused **two deaths** (miners in the operating mine next to the closed one)
- **structural damages** to many buildings and houses.

Example of damages caused by the post-mining EQ in Stilfontein in 2005, Durrheim et al. 2007

European panorama of post-mining seismicity situations



In Germany, in the Ruhr area:

- The **Ibbenbüren coal basin**, mine closed in **2018**;
- The **Hamm Coal Basin**, Bergwerk Ost" (BW Ost) mine, closed in **2010**;

In the Czech Republic, Czech part of the Upper Silesian basin:

- The **Ostrava Coal Basin** closed in **1994**;

In Poland, Polish part of the Upper Silesian basin:

- The **Kazimierz-Juliusz mine**, closed in **2016**;

In France, in Provence:

- **Gardanne coal basin**, closed in **2003**.

Post-mining seismic monitoring ?

National seismic network : all countries → **magnitude ≥ 1 is detected**

Local monitoring networks: **Mine monitoring network dismantled after mine closure**

Gardanne Basin (France):
The **local network still exists** but dedicated to the detection of **mining subsidence** and not to post-mining seismic risk → **Allow to record a magnitude less than 1**

Hamm & Ibbenbüren basins (Germany): network operated by Ruhr University Bochum, **upgraded in 2021**

Kazimierz-Juliusz Basin (Poland): **Local network** has been installed to detect events of lower magnitude as part of the **RFCS PostMinQuake (3 stations)**

Ostrava Basin (Czech Republic): **Post-mining activity detected by the seismic network of the nearby active mine** of Karvina (for the prevention of landslides) poor resolution

No dedicated seismic network for post-mining seismicity monitoring

Main characteristics of the Post-Mining seismicity

Post-mining seismicity observed in all the considered basins

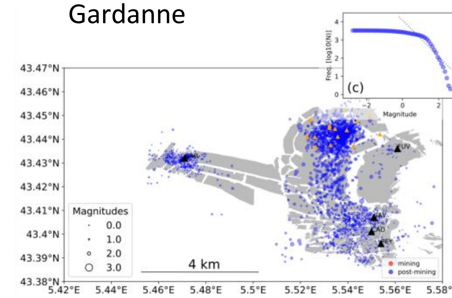
In the basins of Gardanne (closed in 2003), Hamm (closed in 2010) et d'Ostrava (closed in 1994):

- **Magnitude Max** detected ~**3 to 3,5**
- Major seismic events occured **9 years, 4 year and 13 year after closure**
- **Felt seismicity** by the population occur at **shallow depth**

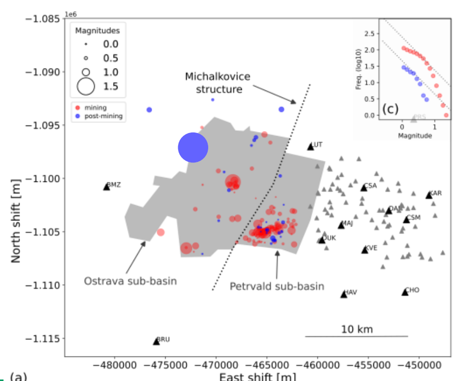
In basins d'Ibbenbüren (closed en 2018) and Kazimierz – Juliusz (closed en 2016)

- Few events, but **magnitude ~ 2**

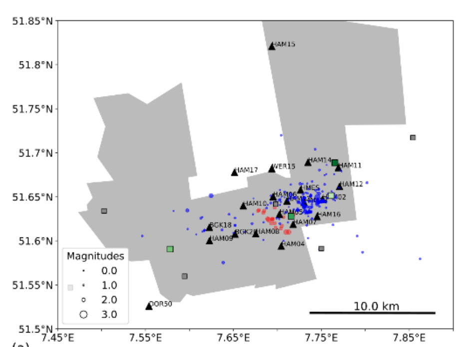
Gardanne



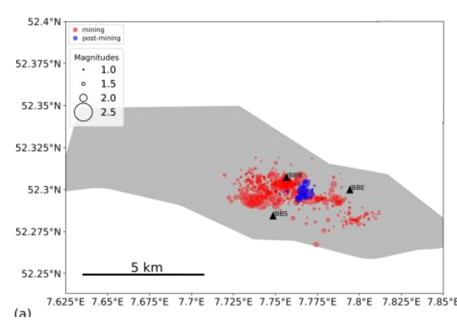
Ostrava



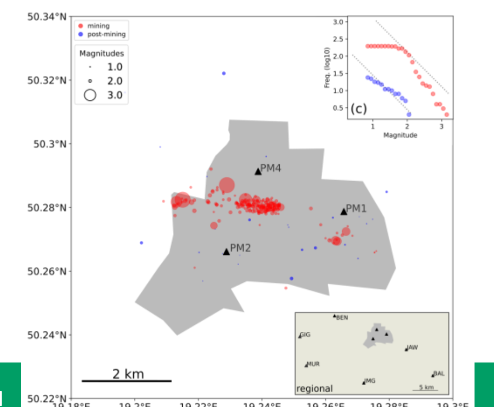
Hamm



Ibbenburen



Kazimierz-Juliusz



Contrucci et al., 2023

Hydrogeological situation

The groundwater level is maintained by pumping in all basins for different reasons:

- to avoid **flooding of nearby active mines** (Ostrava and Ibbenbüren basins)
- to **prevent flooding of the surface** land subsided by mining (Hamm basin)
- to **avoid overflows and visual pollution** (Gardanne basin, to avoid red water discharged into the port of Marseille)
- to **control flooding** in Kazimierz (Kazimierz-Juliusz basin)

→ **Gardanne**: **seismicity strongly controlled by groundwater variations**

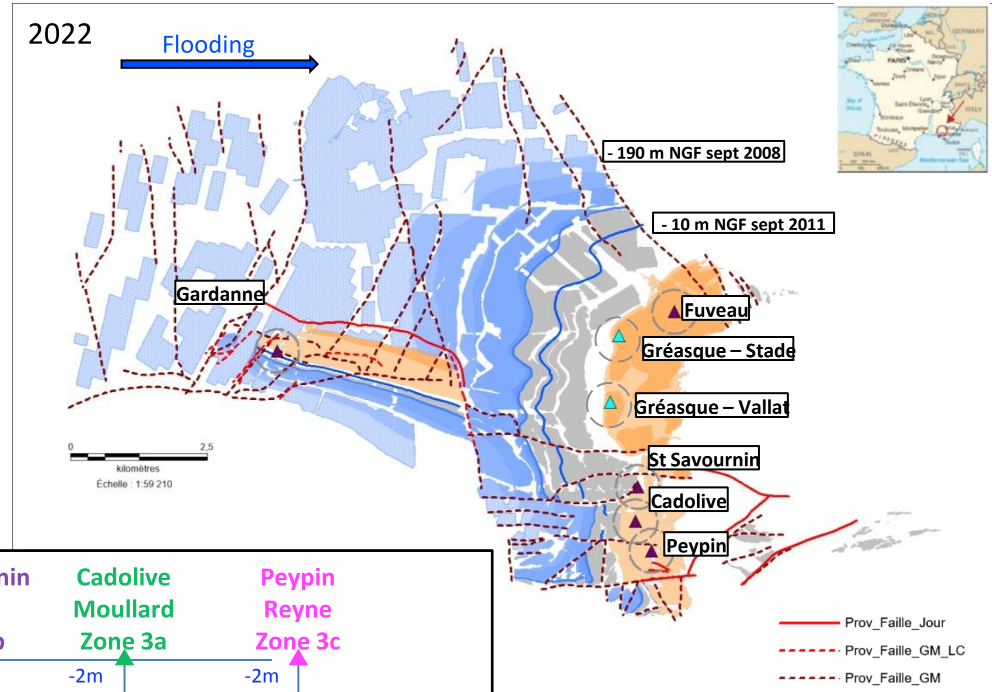
Early warning system to prevent post-mining collapses

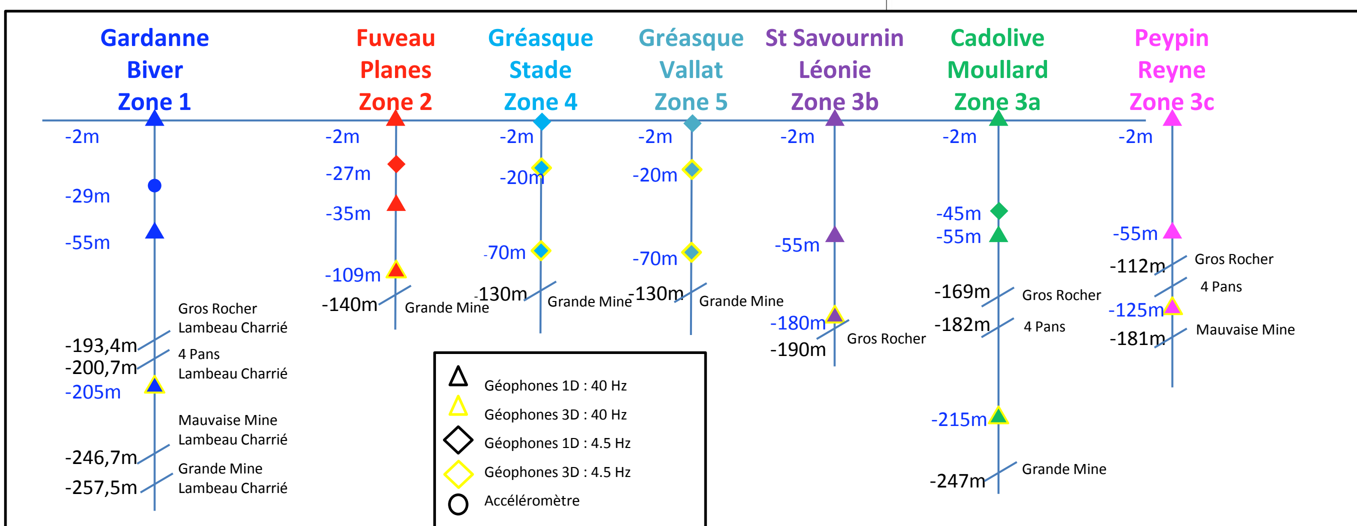
Monitoring performed :

- Early warning system
- 7/7 day and 12/24 h
- Data available 24h/24h on e.cenaris

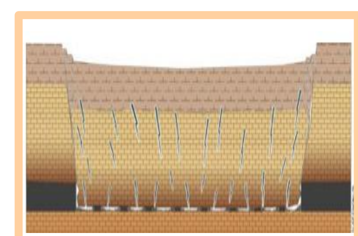
Alarm procedure for public safety

Design to detect early sign of mining collapses





Brittle subsidence
50 < Depth < 250 m

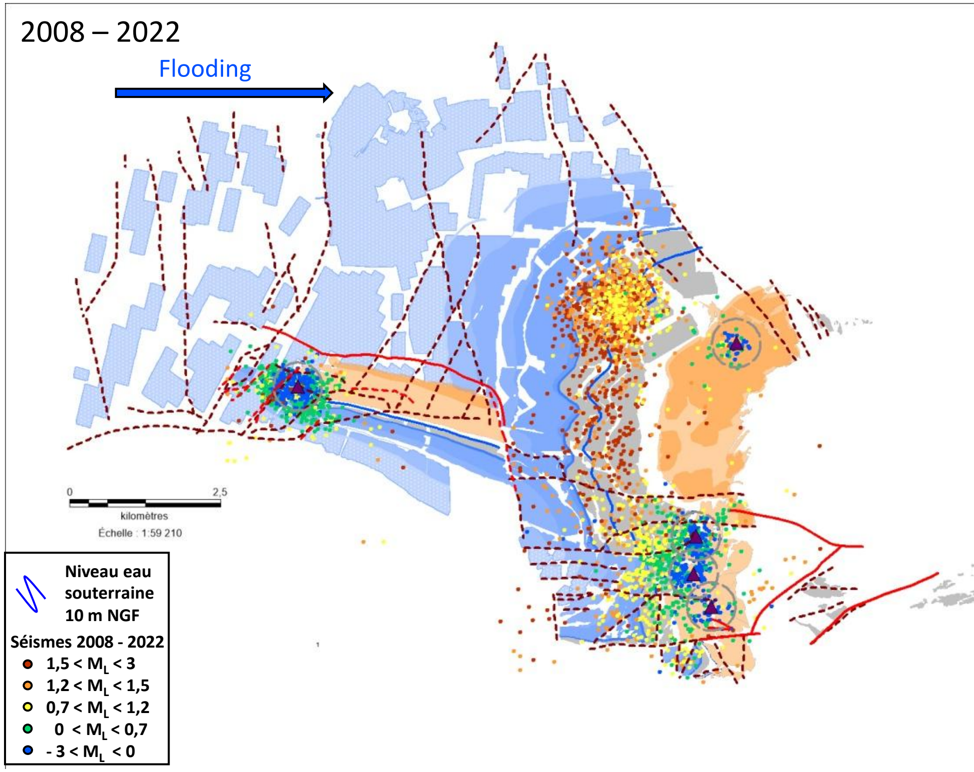


Unexpected Post-Mining seismicity in the closed Gardanne Basin

2008 – 2022: more than **3 700 seismic events recorded**

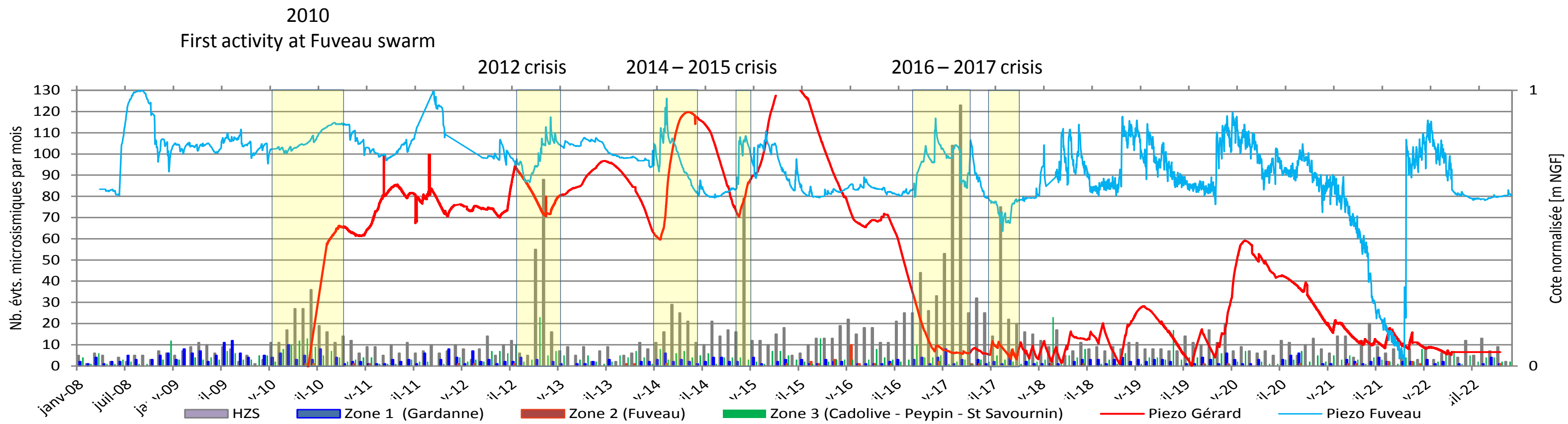
- Magnitude **-3 < M_L < 3,5**
- **Localized along the flooding front** at the center of the basin - « Fuveau swarm »
- **Repetitive seismic episodes felt by the population** in 2010, 2012, 2014, 2016 – 2017

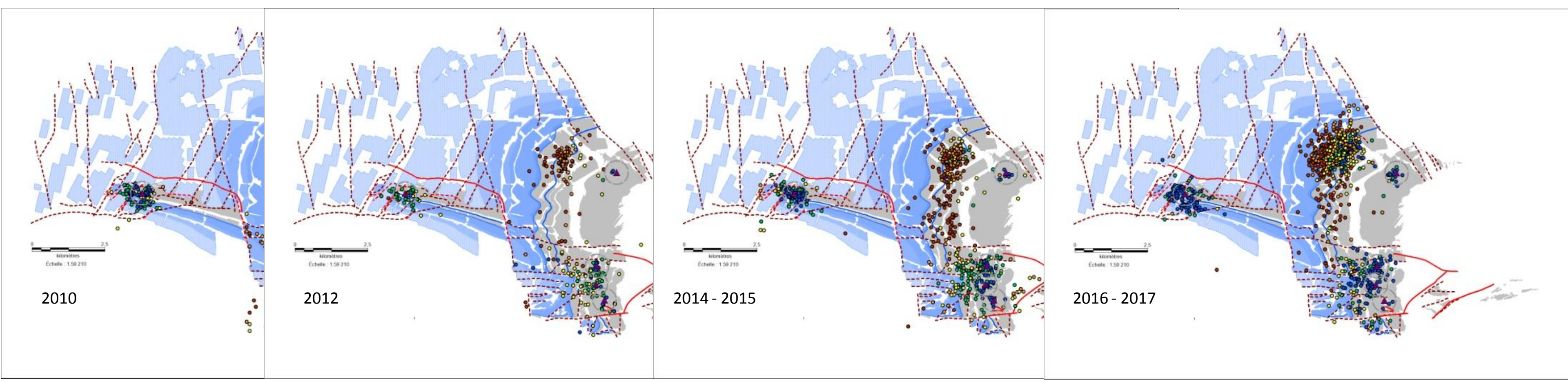
What is the origin of this seismicity?



Seismic activity / underground water level variation

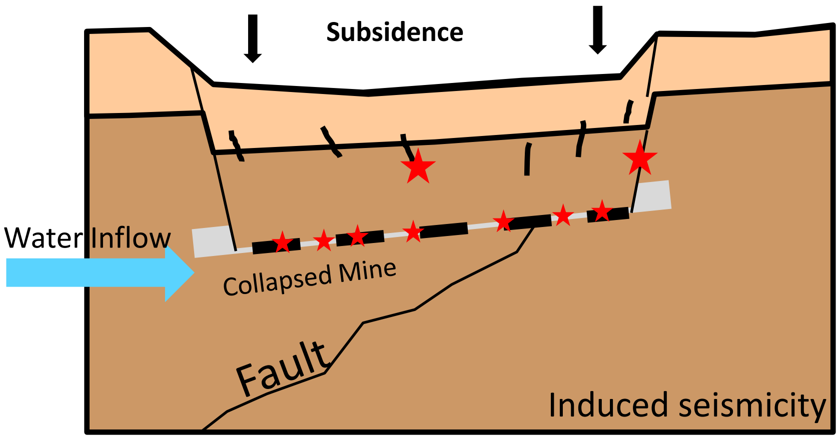
Example of the closed coal basin of Gardanne

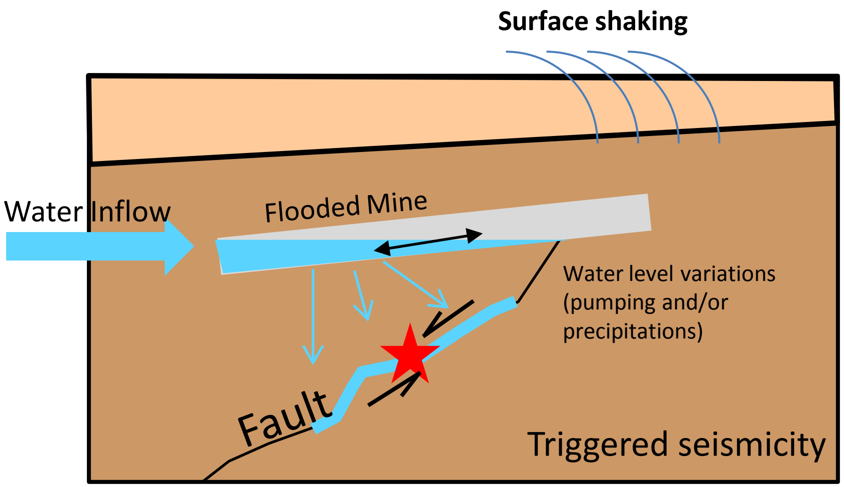




Underground water variation strongly control the seismicity

Hypothesis on the origin of seismicity





<u>Induced seismicity</u>: repetitive mine collapses

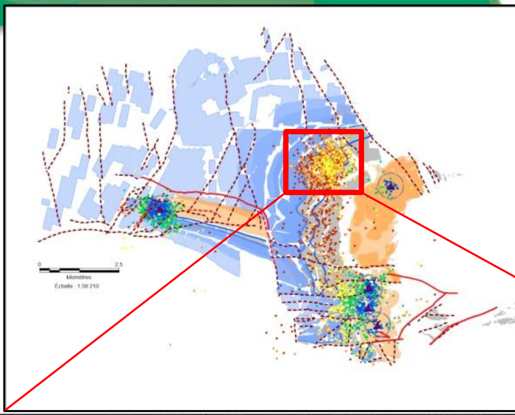
- the **instabilities will one day reach their final stage** (equilibrium) → **end of seismicity** generation;
- the maximum magnitude $\mathbf{M_{max}}$ same order of magnitude as currently measured → **will depend on the size of the collapses,** which, a priori, **will decrease over time**

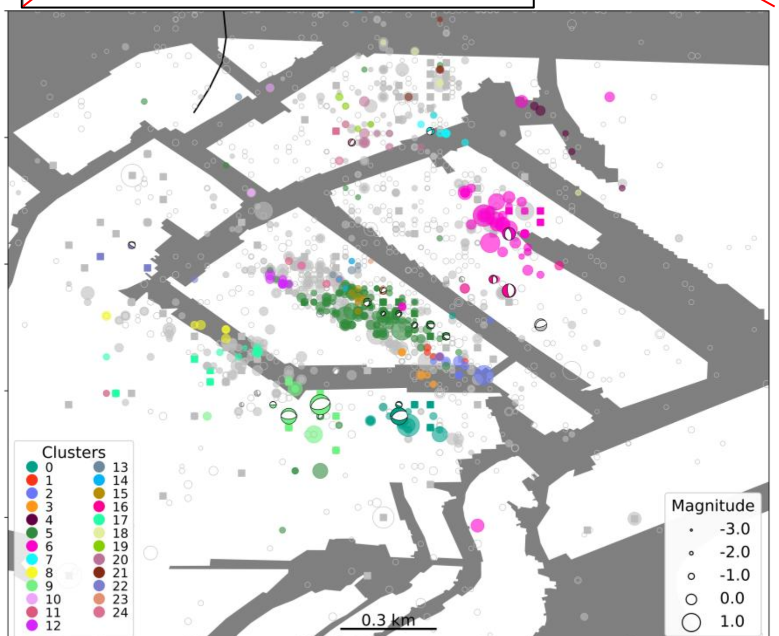
<u>Triggered seismicity</u> : reactivation of faults following hydrogeological modifications

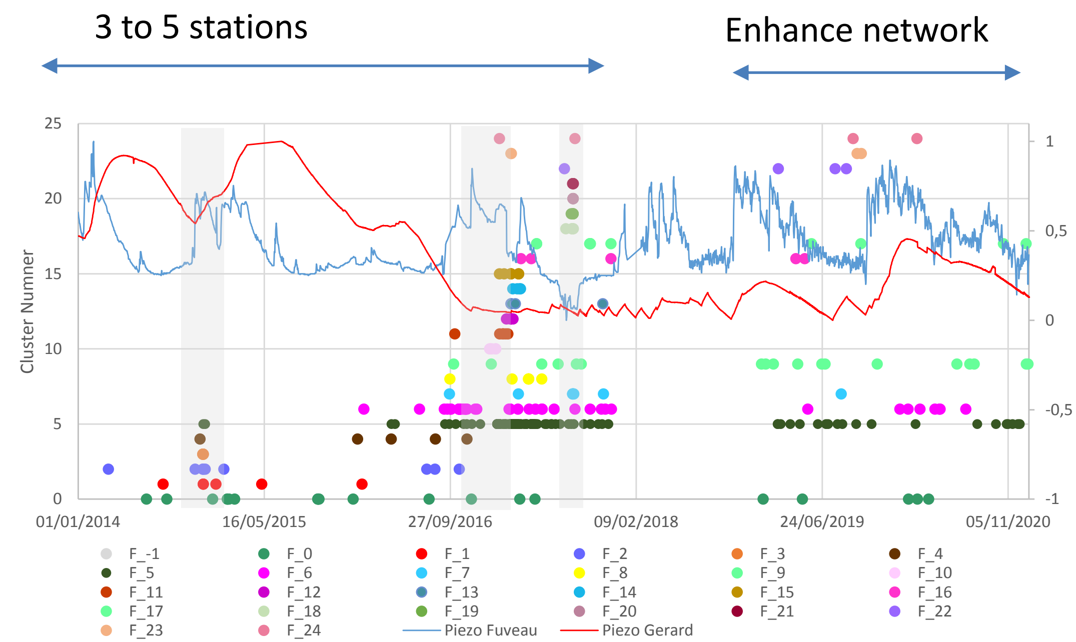
- Mining works: **new anthropogenic aquifer,** modify the state of stress on the fault
- Persistence of **long-term seismicity**
- The maximum magnitude $\mathbf{M_{max}}$ will depend on the size of the fault segment that is reactivated

Seismic cluster analysis

In-depth analysis of seismicity
From temporary network deploy by BRGM and Ineris







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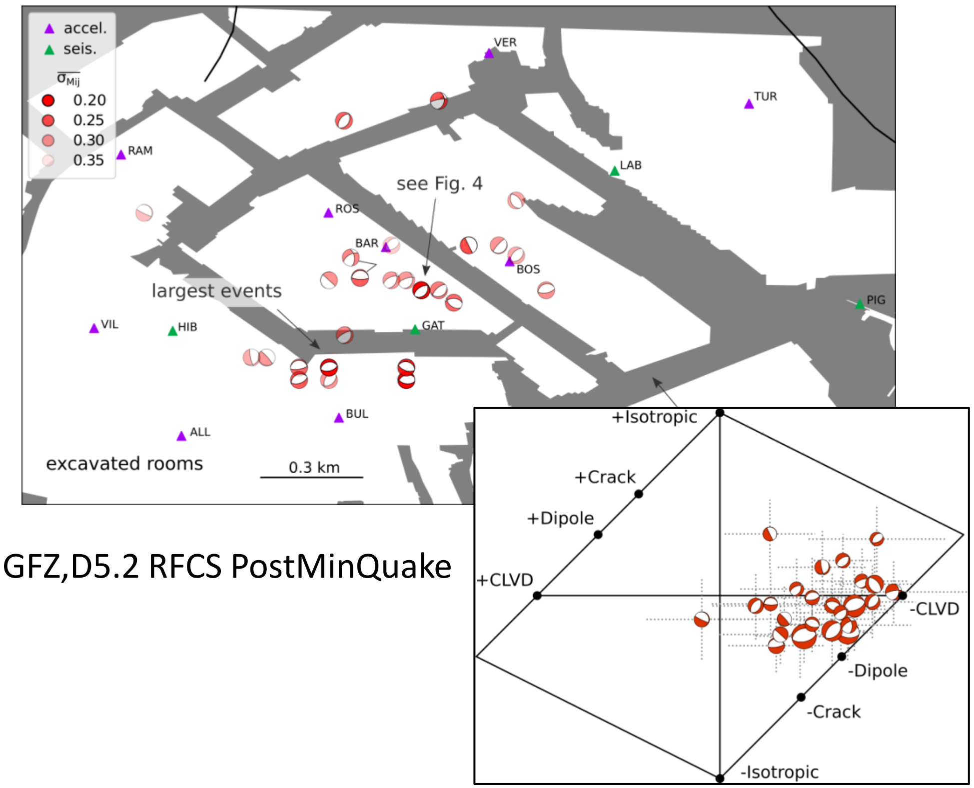
Repetitive seismic activity in accordance with fault reactivation

Source mechanism analysis



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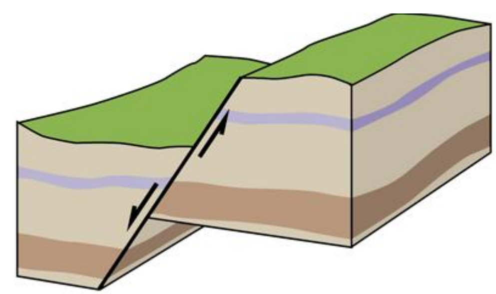
- Calculation of focal mechanisms by total inversion of the waveform
- Performed on a selection of events from 2019 when the network was the densest located in the historical swarms

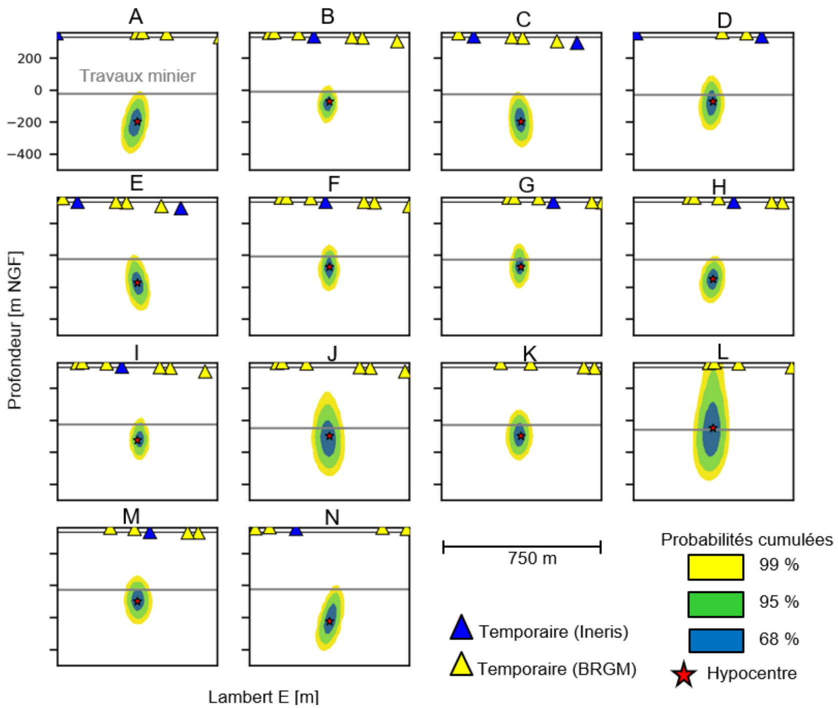
Results

- Predominance of **normal fault mechanism** with variable directions // to existing structures (NW-SE and NE-SW)
- Predominance of double couple mechanisms
- Existence of a negative CLVD component → **compaction**

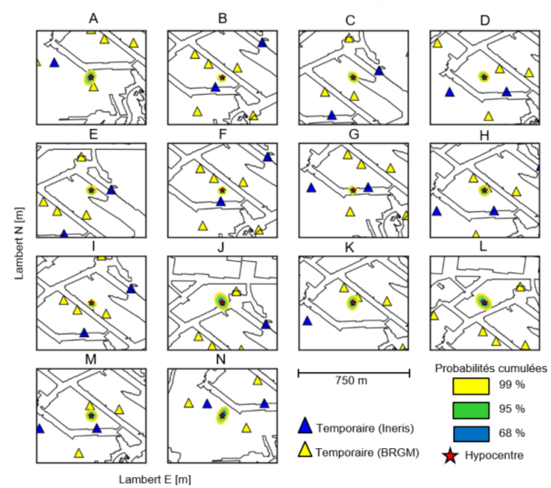


Evaluation of the earthquake's depth

Kinscher et al. 2021, Ineris - 201216 - 2215842 - v1.0



- 14 events from 2019 recorded by the 14 research stations
- **The depths of the 14 events are between 50 and 200 meters <u>below</u> the mine workings**
- A forcing of the location of the events **above** mine workings need to consider a high V_p/V_s ratio (> 2.3) which is not coherent with the stiffness of the limestones



Main Lessons learned

Post-mining Seismological monitoring

- Need to deploy fully dedicated post-mining seismic network

Post-mining Seismic activity

- Observed in **all** considered basins
- Magnitude max 3.5, **felt at the surface** as the EQ occurred at **shallow depth**
- Occurred several years after the closure

Underground Water level variations, play a major role in triggering seismicity

- The presence of mining works acted as an **anthropogenic aquifer**
- **Underground water level variations can reactivate existing fault,** by hydraulic load and discharge, as well as pore pressure variations, which control the state of stress applied to the faults
- **Underground water level is maintained by pumping :** failure causes water level rise → seismicity
- **The presence of water** that triggered seismicity is a main difference with mining seismicity (during the exploitation) in dry environment
- Observed in other context where fluids are involved (Geothermal activity, fluid injection …)

Main Lessons learned

Follow the variations of the groundwater table by installing piezometric sensors at strategic places

How to manage this Post-mining seismic hazard ?
Magnitude Max expected depends on the dimensions of the reactived fault

- Risk assessment in areas of low natural seismicity
- Vulnerability : Shallow post-mining earthquakes
- Optimization of surveillance strategies and the early warning system

RFCS PostMinQuake

Thank you

Isabelle Contrucci
Ineris
www.ineris.fr
Email: Isabelle.Contrucci@ineris.fr

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The project leading to this application has received funding from the Research Fund for Coal and Steel under grant agreement No 899192