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A good practice guideline for managing seismicity induced by deep geothermal operations

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1 CONTEXT

- **Seismicity related to deep geothermal operations is generally of low magnitude** but, in some cases, **these can lead to larger seismic events (M > 2).**

Definition of seismic incident

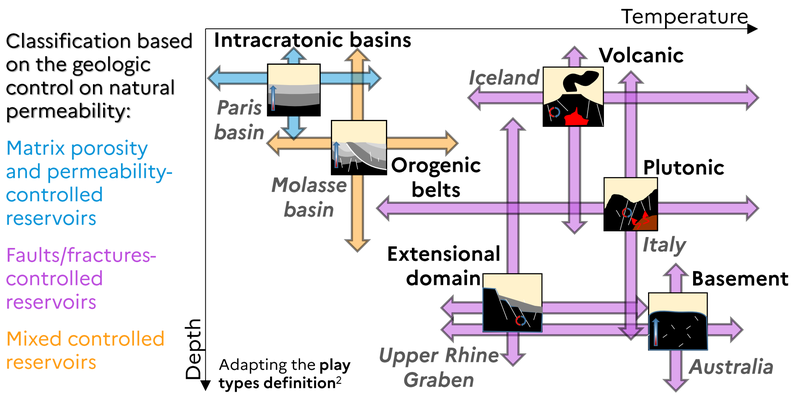
An event whose intensity is likely to **cause nuisance for the population and/or to infrastructures** and **to affect the execution/continuation of the project**

- Seismic incidents (felt or even damaging events) are a **significant concern for the exploitation of deep geothermal reservoirs.**

In this work we present a **good practice guideline for managing induced seismicity hazard related to deep geothermal operations**[1].

2 WORLDWIDE GEOTHERMAL CASE-STUDIES REVIEW

Identify the most relevant intrinsic and operational **factors which influence** the occurrence and the intensity of **induced seismicity**



- Case-studies representative of the different reservoir types and of variable exploitation approaches (non-EGS, EGS, geothermal fields).
- **Case-studies are non associated to seismicity or characterized by one or more seismic episodes** (0.4 ≤ M ≤ 5.5)

Seismic incident hazard

Geothermal reservoir	Intrinsic factors	Operational factors
Matrix porosity and permeability controlled	**Far from the basement without faults** connected to the reservoir	**Without EGS technologies**
Mixed controlled	**Faults** connected to the reservoir, but **not to the basement and non-critically stressed**	**Without EGS technologies**
Matrix porosity and permeability controlled Mixed controlled Faults/fractures controlled	Good hydraulic properties but in **presence of faults, critically stressed and/or connected to the basement**	-
Mixed controlled	Presence of **permeable faults hydraulically connected to more competent rock layers** at depth	**Without EGS technologies**
Faults/fractures controlled	**Low natural fluid flow and/or low injectivity values**	**With EGS technologies**
Faults/fractures controlled	Large amounts of **high temperature geothermal fluids**	**Large volumes and temperature changes**

- Projects can be associated to **different levels of seismic hazard** as a function of their **intrinsic and operational characteristics** and the **type of exploited reservoir**.

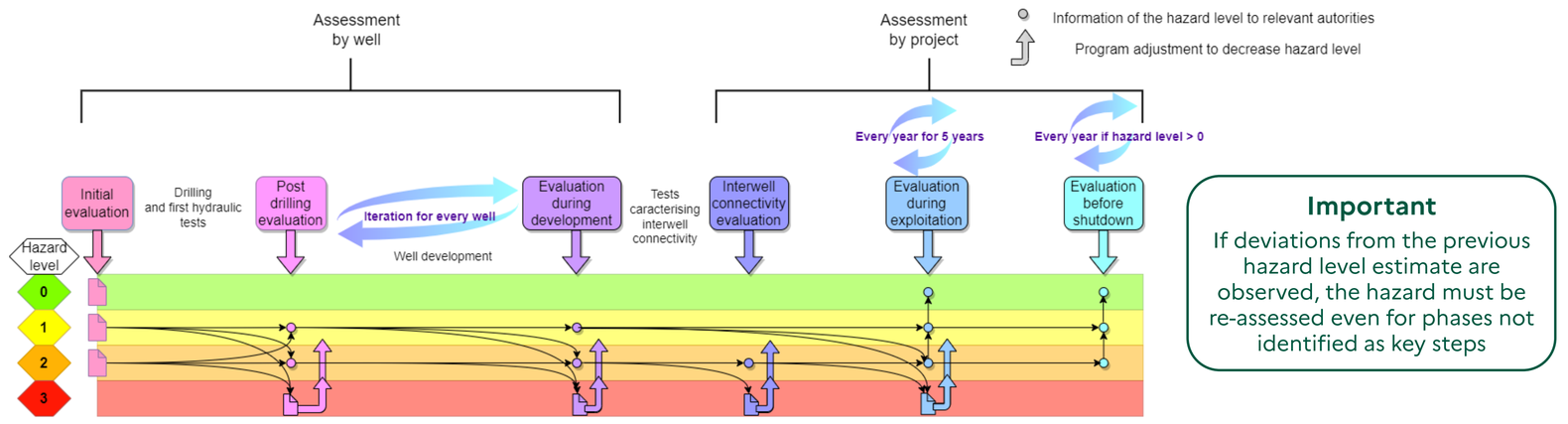
3 METHODOLOGY FOR SEISMIC INCIDENT HAZARD ASSESSMENT

The methodology proposed in the guideline:

- Allows **assessing seismic incident hazard for several key steps of a geothermal project**, throughout its lifecycle.
- Is **applicable to different type of geothermal reservoirs and exploitation approaches** (e.g. EGS and non-EGS).
- Defines four **seismic incident hazard levels that characterize to what extent induced seismicity is of concern.**

Hazard levels	0	1	2	3
Qualification	Very low	Low/moderate		High
Mitigation measures	No measures required	Seismic monitoring and Traffic Light System (TLS)		Adjustment of the work program

- **Hazard levels indicate the likelihood** of a **seismic incident.**
- **Hazard levels are associated to** specific **mitigation measures.**

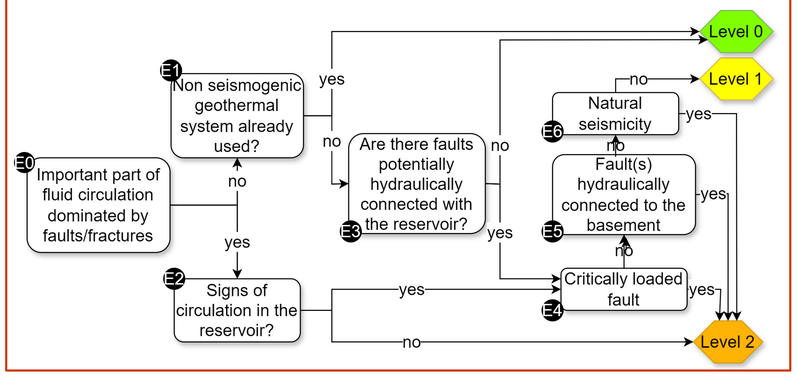


Important

If deviations from the previous hazard level estimate are observed, the hazard must be re-assessed even for phases not identified as key steps

- The **hazard level is updated**, over time, **with the acquisition of new knowledge** about the reservoir and its behavior.
- Well-by-well assessment ⇒ based on logic-trees (see below).
- Project-based assessment ⇒ based on recommendations on how to assess the seismic incident hazard.

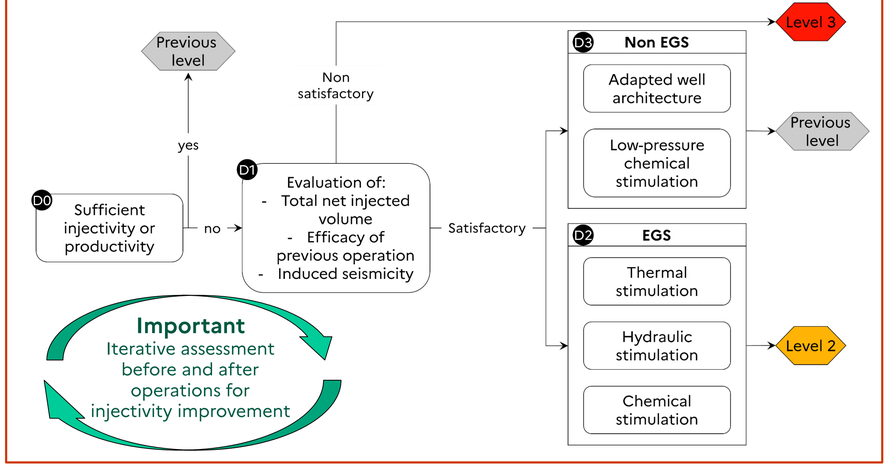
Pre-drilling hazard assessment



Post-drilling hazard assessment

F0 - Critically loaded fault	F1 - Microseismicity during drilling	F2 - "Insufficient" injectivity index	Hazard level
Yes	Yes	Yes	3
		No	2
	No	Yes	2
		No	2
No	Yes	Yes	2
		No	2
	No	Yes	2 ⇒ if EGS 1 ⇒ if non-EGS
		No	1

Hazard assessment during development



Important

Iterative assessment before and after operations for injectivity improvement

- **Logic-trees designed following the geothermal case-studies review** ⇒ including intrinsic and operational factors.
- **Logic-trees account for the interactions between hazard assessment** criteria and **do not require** the definition of **scoring systems**[3,4]**.**

4 RECOMMENDATIONS AND BEST PRACTICES

Data acquisition & management

Recommendations about high-quality data and analyses required, according to hazard level and project phase, **for reservoir characterization and hazard assessment**

Data management following FAIR principles throughout project lifetime

Findable Accessible Interoperable Reusable

Microseismic monitoring

Recommendations about seismic monitoring network characteristics, according to hazard level and project phase

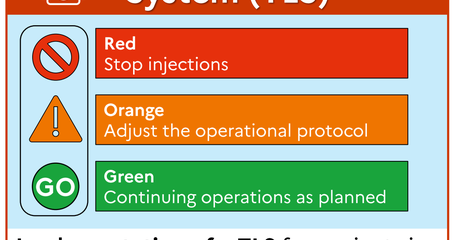
Recommendations about seismic network objectives, design and required technical performances , according to hazard level and project phase

Cross-interpretation of microseismic and operational data over time

Hazard level	Before drilling	Drilling	Development	Exploitation
0	Dedicated seismic monitoring network not required			
1	**Permanent network** 6 months before drilling	**Permanent network + extended network** if: M > 0,5 et PGV > 0,5 mm/s	**Permanent network + extended network** if: Orange TLS threshold exceeded	**Permanent network + extended network** if: Orange TLS threshold exceeded
2	**Permanent network** 6 months before drilling	**Permanent network + extended network** if: M > 0,5 et PGV > 0,5 mm/s	**Permanent network + extended network**	**Permanent network + extended network** if: Orange TLS threshold exceeded
3	**Existing seismic network** in agreement with recommendations for projects in hazard level 1 or 2			

- **Permanent network** ⇒ in operation for **the entire duration of the project** (hazard levels 1 and 2)
- **Extended network** ⇒ additional seismic sensors **at some key steps of the project** or when significant seismicity occurs

Traffic Light System (TLS)



Implementation of a TLS for projects in hazard level 1 and 2

TLS thresholds are **fixed by the operator in agreement with the regulator**

TLS thresholds regularly updated, based on knowledge and information acquired

Red-light threshold coherent with the defined seismic incident intensity

5 CONCLUSIONS

- The **guideline is addressed to all stakeholders** involved in the geothermal energy sector.
- The **purpose of the guideline** is to **provide a framework for mitigating the occurrence of large magnitude events** during deep geothermal operations.
- The **approach proposed** in the guideline **can be applied to different geothermal reservoir types and exploitation approaches** (EGS and non-EGS).
- The **guideline** has been **developed for France**, but it **can be adapted for other countries**.
- The **guideline only deals with hazard**, risk-like aspects, such as exposure and vulnerability, and societal concerns are not included.

REFERENCES

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