

Cross-sites analysis of seismic response in geothermal reservoirs during stimulation and circulation operations

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1 INTRODUCTION & SCOPE OF WORK

The exploitation of deep geothermal reservoirs can be occasionally associated with the occurrence of felt and even damaging induced seismicity, raising concerns for geothermal projects development due to public acceptance and increased seismic hazard. Although mechanisms triggering geothermal-induced seismicity are generally well understood, mitigating high magnitude events remains challenging, since the seismic response is strongly site-specific and variable for different operations at a given geothermal site.

The scope of this work is to compare the seismic response of several deep geothermal projects, in different geothermal contexts, considering the whole injection history for different operations, including hydraulic stimulations and balanced circulations within doublets. We first homogenized seismic catalogues among different geothermal operations, using consistent moment magnitude (M_w) scales. We then analyzed the evolution of several seismic parameters and evaluated existing models for M_{max} estimation, including volume-based (Galis et al., 2017; McGarr, 2014; van der Elst et al., 2016), energy-based (Drif et al., 2024) and time-based (Langenbruch et al., 2024) approaches.

2 METHODOLOGY

We selected 22 operations in 9 EGS and non-EGS projects, targeting both fractured basement reservoirs as well as faulted and karstified sedimentary aquifers (Table 1). Selected operations include hydraulic stimulations, re-stimulations, defined as subsequent hydraulic stimulations in a well already stimulated in the past, as well as short (few weeks) and long-term (several months) circulation phases.

To account for data heterogeneity between different geothermal operations and projects, we homogenized seismic datasets using consistent moment magnitude (M_w) scales.

Based on the homogenized datasets, we analyzed the co-injection evolution of some seismic parameters, such as seismic moment (M_0), moment magnitude, seismogenic index (Σ) and seismic injection efficiency (I_E), and their variability in function of the operation type and with respect to injected volume and hydraulic energy (ΔW_H).

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Table 1. List of the 9 geothermal projects and of the 22 related operations selected in this study. For each operation, the name of the injection well is mentioned along with the year of injection. For circulations, the wells are named as follows: injection well/production well.

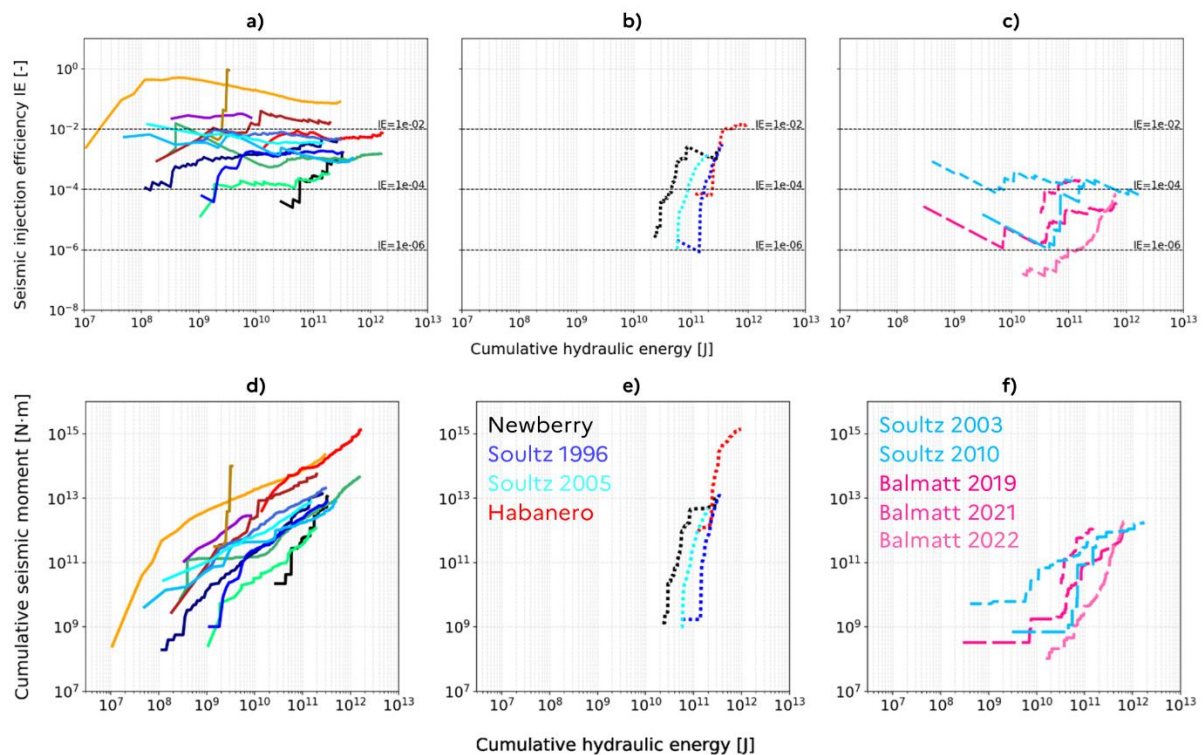
PROJECT	ROCK TYPE	PROJECT TYPE	STIMULATIONS	RE-STIMULATIONS	CIRCULATIONS
SOULTZ-SOUS-FÔRET (FR)	Crystalline	EGS	GPK1 (1993)	GPK2 (1996)	GPK3/GPK2 (2003)
			GPK2 (1995)		
			GPK2 (2000)	GPK4 (2005)	GPK1/GPK3/GPK2 (2010)
			GPK3 (2003)		
			GPK4 (2004)		
RITTERSHOFFEN (FR)	Sedimentary & crystalline	EGS	GRT-1 (2013)	-	-
OTANIEMI (FI)	Crystalline	EGS	OTN3 (2018)	-	-
			OTN2 (2020)		
HABANERO (AU)	Crystalline	EGS	HAB 4 (2012)	HAB 1 (2005)	-
PARALANA (AU)	Sedimentary & crystalline	EGS	Paralana 2 (2011)	-	-
NEWBERRY (US)	Volcanic	EGS	NWG 55-29 (2012)	NWG 55-29 (2014)	-
BASEL (CH)	Crystalline	EGS	Basel 1 (2006)	-	-
ST GALLEN (CH)	Sedimentary	Non-EGS	Gt-1	-	-
BALMATT (BE)	Sedimentary	Non-EGS	-	GT-02/GT-01 (2019)	GT-02/GT-01 (2021)
					GT-02/GT-01 (2022)

3 RESEARCH OUTCOMES

Overall, results reveal (i) common trends in the evolution of some seismic parameters among different projects, despite variability in reservoir properties and injection protocols, as well as (ii) distinct seismic behaviors among variable operations within the same geothermal site.

In agreement with previous studies (Bentz et al., 2020), for stimulations, the cumulative M_0 (and M_{max}), evolve linearly with the cumulative injected volume and the cumulative ΔW_H (Figure 1d). Except for St. Gallen, which is a particular case due to a methane leak coming out of the well, and Newberry, which is the only selected case in a volcanic context, most of the stimulations analyzed start with a sharp M_0 increase, followed by a rather linear slope until the end of the operation. Initial variations in I_E values are followed by a nearly constant evolution throughout stimulations (Figure 1a), except for the previously cited cases of St. Gallen and Newberry, reflecting a stable and relatively predictable reservoir response. In contrast, re-stimulations show a different behavior with respect to stimulations. First, a reservoir memory effect (Kaiser effect) (Baisch & Harjes, 2003) is observed, with delayed seismicity until pressure exceeds the threshold reached in the previous stimulations (Figure 1b, e). Once this threshold is exceeded, M_0 and I_E increase abruptly, reaching values similar to those observed during initial stimulations. Finally, circulation operations generate weaker seismic responses, characterized by sudden and irregular jumps (Figure 1c, f). I_E is generally lower, reflecting less efficient energy release compared to stimulation and re-stimulation operations (Figure 1c).

The evaluated M_{max} estimation models (not shown in this abstract) indicate variable performance among the selected projects, highlighting the limitations of their underlying assumptions. These findings highlight the role of injection history, reservoir seismotectonic state and triggering mechanisms on the seismic response and open the discussion on seismic hazard mitigation strategies adapted for different types of geothermal operations.



Stimulations (a): Soultz 1993; Soultz 1995; Soultz 2000; Soultz 2003; Soultz 2004; Rittershoffen; Otaniemi 2018; Otaniemi 2020; Habanero 2012; Paralana; Basel; St. Gallen; Newberry 2012

Figure 1. Co-injection evolution of the seismic injection efficiency (first row) and the cumulative seismic moment (second row), in function of the cumulative hydraulic energy for stimulations (a, d), re-stimulations (b, e) and circulation operations (c, f). The color code is described in the legend below the figure for stimulations (a, d) and within the diagrams for re-stimulations (b, e) and circulation operations (c, f).

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