Proceedings World Geothermal Congress 2026, Calgary, Canada, June 8—11, 2026

Induced Seismicity – IEA-Geothermal Collaboration on Mechanisms and Public Acceptability for Deep Hydrothermal, Superhot and EGS Systems

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INTRODUCTION

Since 2004, IEA-Geothermal has coordinated joint research and information sharing between member countries (USA, New Zealand, Iceland, Korea, France, Germany and Switzerland), regarding the mechanisms and adaptive management options to address the adverse and beneficial effects of geothermal Induced Seismicity (IS). Research is linked to deep drilling into both moderate and high-temperature hard-rock geothermal systems. The lessons learnt from historical collaborative work of the IEA-Geothermal (WG1 and WG11), and recent work of WG13 –D (IS) in these settings is summarised here. From monitoring of projects, we seek to share knowledge acquired, and inform future endeavour. The objective is to help reduce induced seismicity risks and barriers, both real and perceived, while advancing the demonstrated benefits of improved monitoring and passive seismic processing tools and thereby enhance the global deployment of geothermal energy technology. Through collaborative modelling and data sharing, the key mechanisms behind IS that can accompany long term injection or short-term fracture stimulation are investigated. In operating geothermal systems hosted in fractured reservoirs, monitoring of micro-seismicity combined with seismic tomography (velocity inversion) provides geothermal reservoir modelers and resource managers with improved information on geothermal reservoir behaviour and extent. This information enables production and reinjection strategies to be fine-tuned to improve utilization sustainability. The knowledge gained can also help develop better strategies for risk reduction, inform resource expansion and help choose targets for make-up drilling.

HISTORY

Induced seismicity risk remains an issue for many geothermal projects in different settings. 'Hydrothermal' and 'Superhot' resources may be hosted in volcanic and tectonically active settings, while EGS projects typically access regions of elevated temperature gradient and deep compacted sediments or brittle basement rock such as granite.

To address environmental and social concerns, a series of three international workshops were initially organised between 2005 and 2009 to discuss the issues related to fracture creation for EGS (Baria et al. 2006, Majer et al. 2007). In 2010, it transferred from a sub-task of WG1 to a full Annex activity (Working Group 11). The scope was also broadened to include induced seismicity at conventional hydrothermal projects (Bromley & Majer, 2012).



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EGS STIMULATION

IEA-Geothermal identified induced seismicity as an important community issue for EGS development as early as 2004. Important outputs from early work included a 'Protocol for Induced Seismicity Associated with Enhanced Geothermal Systems' (Majer, et al., 2007). This paper presented a review of the knowledge on seismicity induced by EGS creation and operation. It identified issues which, once addressed, would provide better understanding of the event-generating mechanisms. Induced-seismicity hazards from hydro-fracturing at EGS projects could then be assessed more robustly. For example, the potential IS hazards at a subsequent Australian EGS project (Cooper Basin) were addressed using the protocol. Risk governance was addressed by Kraft et al (2025) and reviews, with good practice guidelines for managing induced seismicity associated with EGS projects, were compiled by Zhou et al (2024) and Majer et al (2025).

It was concluded that EGS-induced seismicity need pose no threat for development of geothermal resources if sites are selected judiciously, community issues are handled effectively, and developers/operators and licensing authorities understand the mechanisms/triggers that cause the events. In fact, detected induced seismicity can be beneficial for the purposes of monitoring the effectiveness of EGS operations and providing information on reservoir processes, as well as relieving accumulated rock stresses. Some of the results and conclusions from this work follow below.

a) When considering sites for EGS development, especially urban locations, it is prudent to consult or, if necessary, acquire new geological and seismological information to gauge suitability in relation to background natural seismicity on active faults, the state of stress and the existence of superficial deposits with potential for amplified ground shaking.

b) With regard to vibration hazard, EGS is similar to other activities such as mining, hydrocarbon production, waste disposal or dam filling operations, where a possibility always exists of higher stress release when a load changes. The seismic frequencies thus generated are generally too high to cause significant structural damage. The defining criteria used for assessing the magnitude of induced seismicity should be ground acceleration and frequency content. For structural damage to occur, frequencies of less than about 10 Hz are normally required. Generally, frequencies associated with induced seismicity are much higher, between 100 Hz and 300 Hz, consequently less likely to cause structural damage, though occasionally larger events generate ~40 Hz waves.

c) Some investigations indicate that the smaller the strain energy placed in the stimulated zone, the smaller the possibility of generating larger seismic events. Pumping at lower pressures over longer periods, or more slowly building up then reducing pumping pressures over the stimulation period, or utilizing thermal stresses by injecting cool fluids at low pressure, may be advantageous.

d) A "Traffic-Light" approach was strongly suggested, whereby communities are assured that high-pressure pumping activities will be amended or suspended if certain levels of large-magnitude induced seismicity are exceeded. The level of acceptability depends on local ground conditions, proximity of buildings, and susceptibility of infrastructure to vibration damage. However, this approach remains reactive. Even if injection is halted after the first felt event, this does not prevent subsequent felt events. The ultimate need, therefore, is an advanced procedure to prevent, or at least reduce, disturbing events (M≥ 3) related to EGS operations. Advanced "Traffic Light" algorithms may use probabilistic forecasting of large events using AI derived predictors (e.g. "DEEP").

e) Note that, to date, there have been only a few cases where a relatively large induced seismic event associated with EGS projects has caused damage. However, public perception is important, and therefore this should be dealt with correctly at the start of a project. Expectations and fears need to be taken seriously. The public should be educated about the advantages and potential adverse effects of fracturing a reservoir and kept informed during the project's implementation.

DISCUSSION : PUBLIC PERCEPTION

Induced seismic events are typically small in magnitude compared with natural earthquakes. But, because of their shallow origin, they can sometimes be felt. In some instances (notably in Basel, 2006), induced seismic events generated public concern resulting from the notion that larger, potentially damaging, events could result from future geothermal activities. By contrast, public apprehension regarding the possibility of increased ground-shaking caused by induced seismicity in conventional geothermal projects is usually minimal because the induced seismicity is rarely felt and because there have been no instances of significant damage from induced events. Indeed, local communities in tectonically active areas are usually quite familiar with feeling small, natural earthquakes. It is therefore rare to see constraints on conventional geothermal developments imposed by publicly perceived risks associated with large induced seismic events. Of the 100's of developed geothermal reservoirs worldwide with associated seismicity, only a few have produced induced seismic events of a magnitude felt by people during normal operations. Examples like events at The Geysers (California, M4.6), and Rotokawa (NZ, M4.1) have caused neither significant damage nor curtailment of reservoir operations. Recently, however, attention has focused on the substantial heat resources available globally at depths of 3-10 km, and their potential for energy extraction. EGS techniques can provide access to this heat by enhancing fracture permeability through high-pressure pumping of cool water inducing local micro-seismic events. Because naturally occurring earthquakes are less common in these settings, far from plate boundaries, public perception of the risk of large induced seismic events can be a much bigger issue.

CONCLUSION

The enhancement of reservoir permeability by stimulating or creating fractures through hydro-fracturing, or by stress disturbance from production/reinjection operations, can induce micro-seismic events, which can sometimes be felt. Typically, these are not sufficiently large, nor of the right vibration frequency, to cause structural damage. But occasionally, they can. Seismicity triggers, which include hydraulic pressure and temperature changes, decrease away from a well, and dissipate with time, depending on the permeability. A volume ('cloud') of induced seismic events therefore typically forms progressively around an injection point or in a volume of flowing fluid (injectate or recharge). The degree and extent of stimulation can depend on pressure, temperature and total volume of fluid injected. Stress redistribution over a larger volume of rock may also result from local hydraulic or thermal stress fracturing and could trigger events on more distant faults or fractures that are naturally pre-stressed to near-failure conditions. Monitoring of IS at several EGS sites has shown that many of the larger felt events (M3 to M4) tend to be located at or beyond the edges of the seismic 'cloud' of small events, occurring significantly later than injection rate changes. It may thus be difficult to determine whether a particular seismic event was caused by a particular stimulation process. Importantly, however, the triggering of such events can be viewed as a premature stress release mechanism allowing small movements on larger faults and helping prevent much larger natural earthquakes. All these factors make it difficult to recommend a universally applicable procedure for managing fluid injection that both minimizes risks and maximizes benefits. However, current EGS sites are implementing lessons learnt for effective management of IS.

Acknowledgements

The authors acknowledge the enthusiastic support of past and present IEA-Geothermal Executive Committee Members, and collaborators within IPGT, for the past 20 years of joint work on the topic of geothermal induced seismicity.

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