GEOTHERMAL INDUCED SEISMICITY – RISKS AND REWARDS

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ABSTRACT

A review has been undertaken of international experiences in geothermal induced seismicity, from both conventional operating projects and stimulation (EGS) projects. From a number of case studies, the review reached conclusions that, we hope, will assist developers and regulators manage this issue in a pragmatic manner, while enhancing fracture permeability and thereby energy recovery.

Injection or extraction of fluid induces changes in reservoir pressure and temperature which perturbs in-situ stress conditions. This may be sufficient to trigger seismicity through a range of mechanisms. Understanding of the mechanisms involved has now advanced to the stage that mathematical models have been developed to simulate the processes. The phenomenon of post shut-in seismicity, for example, has been simulated.

In many cases, the maximum magnitude of the induced events appears limited by the geometry of the volume of the stimulated reservoir. This leads to the conclusion that monitoring the spatial growth of seismicity in real time can help constrain the risk of inducing large damaging earthquakes on nearby faults. For site risk assessment, the level of background knowledge regarding natural rates of seismicity, in-situ stress state and rock strength parameters is important.

Ongoing collaborative research, through IEA-GIA Annex XI and IPGT working groups is addressing outstanding issues with the objective of revising existing protocols, and reducing the risks. Key outstanding issues include: discriminating natural from induced events, thermo-elastic effects from long-term production-induced cooling, the effective extent of stress-field perturbations, the choice of stimulation methods to minimize ground shaking, and ways to reduce uncertainties in forecasts of induced seismicity effects.

1. INTRODUCTION

1.1 Background

Injection or extraction of fluids from geothermal reservoirs can change reservoir pressures and temperatures sufficiently to perturb in-situ stress conditions and cause or trigger seismicity (Cladouhos et al., 2010). Such events can be associated with conventional geothermal projects involving low pressure fluid production and injection, or with EGS (Enhanced Geothermal System) projects involving high pressure injection stimulation.

Many conventional geothermal fields have been producing for more than 25 years, but in the majority of cases there have not been any reports of felt induced seismicity. In the few cases that have, seismicity has generally consisted of small or micro-earthquakes. The maximum magnitude measured was 4.6 (at The Geysers, California). With respect to EGS projects, there are no known cases of induced earthquakes in EGS settings from high pressure stimulation or injection causing severe damage (Majer et al., 2007; Baria et al., 2006). However, there is potential for some felt events to be large enough to increase public anxiety, as well as to cause minor damage to infrastructure and buildings. Protocols to deal with this issue, especially in terms of information collection and public dissemination, have already been developed and published (Majer et al., 2008, 2011), and these have benefitted from international collaboration through Annexes I and XI of the IEA-GIA (e.g., Bromley & Mongillo, 2008).

On the positive side, the primary benefit of induced seismicity is an associated increase in permeability (productivity or injectivity), and thereby the extraction rate of heat-energy. This is the reward. The risk is potential earthquake damage. From the operator's point-of-view, in terms of reducing the risk of potential induced seismicity damage, while enabling the benefits, the controllable factors are generally limited to: site-selection, injection pressure and temperature, fluid volume, pumping duration, and pump ramping rates. In practice, uncertainties and variable geological settings, makes it difficult to establish reliable correlations between the level of seismicity and any of these controllable factors. According, it is not currently feasible to apply consistent guidelines for pump operation (for example) in new geothermal settings. Advances in research, and analysis of case studies (such as undertaken for this review, for example), are, however, providing some valuable insights. Hopefully, these will make such guidelines and associated protocols much more of a practical tool in the future.

1.2 Mechanisms

In recent years, understanding of the mechanisms involved has advanced significantly. For example, mathematical models have now been developed to simulate the coupled geo-mechanical and fluid-flow processes (e.g., Baisch & Voros, 2010, McClure & Horne, 2010, Ghassemi et al., 2007).

Levels of induced seismicity (number and magnitude) depend on natural settings: the local stress and friction coefficients, and fault orientations and locations. In active tectonic settings, high levels of natural seismicity are common, faults may be pre-stressed, and seismicity may be triggered by induced stress changes. When fluid pore pressure is great enough to overcome the normal stress, then shear failure can occur. Alternatively, a small change in pore pressure may cause asperities (or locked points) on the 'rough' pre-stressed fracture surface to fail, thereby triggering a seismic event.

There are several other factors affecting the likelihood of induced seismicity that need to be considered in terms of mechanisms. They are: a) displacement stresses from volumetric contraction caused by fluid extraction; b) thermal stresses created by injection of cool fluids into hot rock; and c) chemical stresses associated with injection of brines or acid fluids, causing rock weakening.

The following two sections summarize information distilled from numerous references; space precludes listing them all here. Examples and case studies of geothermal induced seismicity are presented, firstly from operating (or conventional) geothermal developments, and secondly from EGS developments. Lessons learnt from these examples are then summarized (in sections 4 to 6).

2. CASE-STUDIES OF INDUCED SEISMICITY FROM OPERATING GEOTHERMAL SYSTEMS

In Iceland, seismicity occurred during deep injection at Svartsengi, and, in 2011, within geothermal fields in the Hellisheidi-Hveragerdi-Hengill area. In Italy, seismicity (maximum magnitude M3) has been recorded at Larderello-Travale, a steam-dominated system, in response to steam condensate reinjection, and in three other nearby geothermal areas in response to injection. In Olkaria, Kenya, induced seismicity (maximum M1.5) was correlated to discharges from a production well in 1997.

In New Zealand, cases of induced seismicity were observed during high pressure injection trials at Wairakei in 1984, and, since 2006, during routine deep injection (at low well-head pressure) of separated brine into high temperature reservoir formations at Rotokawa, Mokai and Karapiti South (between Wairakei and Tauhara). The seismicity was either adjacent to, or beneath, the area of injection, or was located on pre-existing fracture zones situated along the flow-path between injection and production sectors.

These New Zealand geothermal systems are hosted within the tectonically-active Taupo Volcanic Zone, where high levels of natural seismicity, displaying both time- and spacial-clustering characteristics, make it difficult to distinguish induced from natural seismicity. The following case studies, originating from California, El Salvador and the Philippines, are also hosted in tectonically-active areas.

2.1 THE GEYSERS, CALIFORNIA, USA

Approximately 1000 seismic events are located per year (M>1.5) at 'The Geysers'. Typically, 1 or 2 per year have been of magnitude M>4 (maximum 4.6). Triggering of micro-earthquakes by large regional earthquakes is also observed. Rates of seismicity are correlated with steam extraction and increasing injection rates of cool water. Initially this was surplus steam condensate, but in 1997 and 2003, it was supplemented by treated waste water from nearby towns. Despite this, the mass involved still does not fully replace the mass extracted and lost to the atmosphere (through cooling towers).

Reservoir steam pressure has been in decline since production started, but seismicity was located throughout production zones. Therefore, a simple mechanism of hydraulic shear failure due to pore pressure increase is not favored. Various seismic triggering mechanisms are thought to be responsible. These include pore pressure changes, cooling contraction, and volumetric decline from net fluid loss and associated stress changes.

An approximate correlation was observed between annual injection volume and induced seismicity rates (1000 events of M>1.5 for every 1.3 M-tonne of injection per year). However, other factors clearly have an important role to play. Under constant injection conditions, small fluctuations in pore fluid pressure lead to seismic activity, which locally inhibits further activity (dilatant hardening). Rapid injection locally overcomes dilatant hardening, and triggers more earthquakes through pore pressure diffusion.

A statistical study found that shallow seismicity was initially correlated to production rather than injection, with a lag time of ~1.5 years consistent with pressure diffusion rates between main fractures. Poro-elastic reservoir contraction increases shear stresses across fractures above the reservoir, leading to shear failure (and surface subsidence of up to 1 m per 20 years).

The mechanism for deeper seismicity was thought to be a mixture of thermo-elastic stress due to evaporative cooling of boiling residual pore fluid, and thermal stresses associated with advective cooling from injected fluid. A 'donut' region of low seismic density surrounded by higher seismic density recently appeared in the high temperature zone underlying the NW sector, an area of high volume injection. Local de-coupling between injection and induced seismicity may reflect accumulation of injectate as plumes in the steam reservoir.

In summary, because of a diverse set of mechanisms, and changing pressure, temperature and liquid/vapour phase states, it is difficult to draw consistent conclusions regarding the specific causes of ongoing induced seismicity at 'The Geysers'.

2.2 COSO, CALIFORNIA, USA

At Coso, a direct correlation between the locations of micro-seismicity and the injection and circulation of geothermal fluid was observed. There was also an observed spatial correlation of geothermal development activity with natural seismicity extending southeast of the field. Areas of high seismicity are interpreted to indicate pre-existing fracture zones and dominant flow paths. They also infer different stress patterns within the field. The different stress regime observations are consistent with focal mechanisms, and support an explanation that different stress patterns are associated with fault-bounded geological blocks. Thermal stresses also appear to play an important part in explaining induced seismicity, in particular an observed delay between injection and seismicity.

2.3 BERLIN, EL SALVADOR

Berlín is also located in a seismically active region, so it is difficult to differentiate between natural and induced or triggered seismic events. Seismicity in the reservoir increased after the occurrence of two large nearby tectonic earthquakes in early 2001. Fractures within the Berlin reservoir apparently have a poor capacity to accumulate large amounts of stress; therefore strain energy is released frequently through natural swarms of low-magnitude events. However, some micro-seismicity is spatially correlated to areas of pressure and temperature change, in both production and injection areas, although there was no clear correlation in timing found between the monthly seismicity data and the monthly mass injected or extracted.

A high pressure stimulation experiment was conducted in 2003 at Berlin. A calibrated real-time ‘traffic-light’ control system was put in place to limit injection stimulation operations if the levels of vibration (peak ground velocity) from injection-induced seismicity exceeded acceptable levels. This took into account the stability of local rural housing and shallow ground conditions. The thresholds were not exceeded, and the project was not adversely affected.

2.4 PALINPINON AND TONGONAN, PHILIPPINES

During the first few years of production and injection for the Palinpinon 1 project (1983-86), a significant increase in the level of induced micro-seismicity was observed (M<2.5). Some were felt within the project due to their shallow depth (1-4 km) and proximity. There was an observed correlation in space and time between swarms of micro-seismic events (up to 100/day) and changes in injection and production rates. Event hypocenters were distributed on fractures throughout the pressure-affected parts of the reservoir, but were not noticeably concentrated on major permeable fault planes.

After 1986, the level of locally induced seismicity declined to natural background levels, despite steadily increasing mass flows and lateral pressure gradients, as production doubled in capacity. In 2007, a magnitude M5 earthquake, deemed to be of tectonic origin, occurred at shallow depth within the bore-field. It was triggered by an earthquake 70 km below the bore-field, originating one minute earlier. The shallow event briefly tripped some of the generating turbines because of vibration sensor control, but caused no damage to the geothermal field infrastructure or nearby domestic dwellings.

At Tongonan, Leyte, in 1997, high-pressure, cold-water, hydraulic stimulation of well MG2RD induced seismicity in the high-temperature zone at 2-4 km depth beneath the adjacent Mahanagdong production sector. The induced seismic swarm followed an ENE trend between the injection and production wells, oblique to the trend of the major tectonic structural feature intersected by the well, which is the locally impermeable, NW-SE trending, Central Branch of the transform Philippine Fault. This example shows that major regional faults are not necessarily susceptible to triggered seismic failure through stimulation by high-pressure fluid injection. Local stress conditions may instead favour failure along fault zones of different orientation.

3. CASE-STUDIES OF INDUCED SEISMICITY FROM ENHANCED GEOTHERMAL SYSTEMS

EGS fracturing experiments may involve small volumes of high pressure injection to induce rock failure, or larger volumes of fluid injection at lower pressure, and longer-term circulation tests. Seismicity can be triggered directly by fluid flow, or through changes in pore pressure on fractures, or transient thermal stresses associated with cooler fluids.

During EGS reservoir stimulation, hydraulically-induced tensile rock failure may occur if the fluid pressure exceeds the rock fracture gradient. However, shear failure is more often observed, typically at much lower fluid pressures. Shear failure is, in essence, a triggered seismic release of naturally pre-stressed fractures. Small increases in pore pressure or thermal contraction trigger a release at asperities on fracture surfaces. These triggered events are similar in appearance to natural earthquakes. They have moment magnitudes that are dependent on the magnitude of local stress release and fracture surface area, rather than on the amount of fluid pressure increase.

The maintenance of EGS reservoir permeability during long-term circulation may be further enhanced by triggered seismicity that continues throughout the project lifetime. The mechanism involves gradual stress changes associated with slow cooling, and pressure diffusion into low permeability reservoir rock. This, again, is the potential reward of induced seismicity, but it comes with ongoing risks. The next seven case studies illustrate the similarities and differences in mechanisms across a wide range of induced seismicity experiences at EGS projects.

3.1 FENTON HILL, NEW MEXICO, USA

The majority of the observed seismicity in 1983 at Fenton Hill project (~8000 events) was attributed to shear failure. Occasional tensile fracturing was observed during the early stages of injection, when fluid pressures were high enough. Many shear events occurred in close proximity to those few tensile events. They also occurred at locations where fluid pressure was sufficient to trigger shear failure, but insufficient for tensile failure.

Analysis of the results showed that seismicity was found to occur along pre-existing fracture surfaces that were favorably oriented with respect to the in-situ stress-field. This allowed shear slip. The fracture plane with the highest ratio of shear to normal stress acting along the plane was the one most likely to slip, and events occurred when the normal stress on such a fracture plane was sufficiently reduced by an increase in pore fluid pressure.

3.2 ROSEMANOWES, CORNWALL, U.K.

High pressure fracture stimulation was followed by fluid circulation at 2.2 km depth in a granite batholith. During the first injection phase, micro-earthquakes were observed at low flow rates and wellhead pressures of 3.1 MPa. During the second injection phase (up to 14 MPa) a downward migration of event locations was observed, although seismic activity was less intense, implying stresses had already been reduced. The induced seismicity outlined volumes of rock with increased fracture apertures and permeability. Despite the occurrence of felt events, there were no complaints from residents, possibly as a result of early public education initiatives. The maximum observed magnitude (M1.9) was less than the predicted maximum magnitude of M3.5, which had been determined using a seismic risk assessment based on a predicted maximum affected fault length of ~100 m.

3.3 HIJIORI, JAPAN.

EGS experiments at ~2 km depth, in granodiorite basement, found that the induced seismicity is dependent on the injection rate and wellhead pressure. A time lag was observed between changes in the injection flow rate and the corresponding changes in seismicity. This was interpreted to indicate that the seismicity is correlated to diffusion of pressure transients along fractures.

The induced seismicity is caused by shear failure as the result of slip on joints. This occurs when the effective stress is reduced by increasing the pore fluid pressure. The spatial orientation of the induced seismicity was coplanar with the caldera ring fault structure, suggesting a pre-existing fracture zone was being re-opened and expanded. Shear failure allowed existing fractures to open in the direction of the maximum principal horizontal stress.

3.4 SOULTZ, FRANCE

EGS research in the granite of Soultz, an area of minor natural earthquake activity in the Rhine Graben, involved hydraulic stimulation at 3.5 km, then at 4.5 to 5 km depth, and then fluid circulation. The largest events were M1.9 during the initial stimulation and M2.9 during deeper stimulation. Although no structural damage was caused, public complaints led to restrictions on subsequent stimulation options.

Injection stimulation of the first well GPK1 induced fracturing at differential pressures of up to 7.5 MPa. Micro-earthquakes started 17 hours after injection commenced, and produced a sub-vertical seismic ‘cloud’, ~1 km^3 in volume.

Stimulation of GPK2 at up to 50 l/s (25 kT total) and up to 14 MPa generated most seismicity during the first 4 days of injection. After injection shut-in, the proportion of events with magnitudes >2 increased. This increase in magnitude with time was attributed to a geometrical effect, where stress criticality is approached over a larger reservoir volume, and therefore larger fracture area.

Stimulation of GPK3 at 50 l/s (pulsed up to 90 l/s, 37 kT total) and 16 MPa (pulsed up to 19 MPa) caused the largest three events (up to M2.9) to occur several days after the stimulation ended. This illustrated the apparent limitations of a ‘traffic light’ protocol when applied to injection activities for risk management.

Stimulation of GPK4, at 30-45 l/s and 14-18 MPa (22 kT), triggered events, after the first day, of up to M2.7. Following each shut-in, the numbers of induced events decayed exponentially with time. As with natural seismicity, the induced seismicity tended to occur in temporal swarms.

Subsequent fluid circulation tests undertaken in between the Soultz wells resulted in several hundred locatable micro-earthquakes of up to M2.3. All tests were found to stimulate the same reservoir zones. Each test used different parameters (e.g. number of wells involved, artesian or pump-assisted circulation, and duration), illustrating that induced seismicity can occur under a broad range of operational conditions.

Some events were generated by seismic slip on sub-vertical, hydrothermally-altered, cataclastic shear zones. These zones contain numerous limited-scale fractures with evidence of past movement from slickensides. They are optimally oriented for strike-slip shear failure in the prevailing stress field. A downward progression of the induced seismicity with time was also observed. Permeability was initially relatively low. Induced seismicity created a self-propped, high-permeability flow path, opening up vertical pathways, and facilitating downward penetration of fluids and further seismicity. The micro-earthquake distribution indicates that fluid has penetrated along existing structures with enhanced permeability.

3.5 COOPER BASIN, AUSTRALIA

At Cooper Basin EGS project, granite basement is at ~3.6 to 4.6 km depth; the stress regime is over-thrust; the minimum stress direction is mostly vertical; and induced fracture planes are therefore mostly horizontal. The maximum rock temperature is 264°C. Pumped stimulation has had moderate success (up to 25 l/s discharge at 210°C).

Stimulation of the first deep well (HB1) created induced seismicity at up to M3.7, forming a horizontally-oriented reservoir, ~0.6 km^3 in volume. The in-situ fluid is at an excess (artesian) pressure of 35 MPa. No surface damage was reported as a result of the larger events; the site is remote and there is little community concern. Seismicity was observed to migrate away from the injection well with time. With ongoing stimulation, previously activated regions became seismically quiet (Kaiser effect), because of a stress relaxation process. Induced seismicity from repeat stimulation was not detected until a day after the re-start of injection, and it started at the outer boundary of the previously activated zone, but following the same sub-horizontal structure.

Interpretation of the results suggests that induced seismicity results from fluid overpressure relative to the local stress state, and is generated by slip, or failure of asperities along existing fractures. No direct relationship between the magnitude of the events and the injection records was observed. Some larger events occurred after shut-in, suggesting that the initial stress state of fractures, rather than the pore pressure amplitude, is the critical parameter. It was tentatively suggested that some of the larger events broke a hydraulic barrier, allowing extension of the seismic event ‘cloud’ into previously quiet zones.

3.6 BASEL, SWITZERLAND

Within the city of Basel (an area of natural seismicity in the Rhine Graben), drilling (to 5 km) and high pressure EGS stimulation (up to 50 l/s, at 30 MPa WHP) resulted in several felt events (up to M2.6). Consequently, and following a “traffic-light” protocol, pumping was stopped. Events of M2.7 and M3.4 occurred in the subsequent 24 hours. Well head pressures were later reduced by bleeding off. After a detailed seismic risk study, and observations of minor crack damage to buildings, the project was suspended.

During stimulation, a steady increase in seismicity rate and magnitude was observed with increasing flow rate and wellhead pressure. When the well head valve was opened to bleed off the pressure, a third of the injected water flowed back. This resulted in decreased rates of seismicity. However, sporadic micro-earthquake activity, (< M3.2), was still being detected in the stimulated rock over the next 2 years. The on-going seismicity after shut down and pressure leak-off suggests longer-term stress adjustments had occurred in response to slow pressure diffusion or temperature changes. These experiences reduce the apparent viability and effectiveness of a simple traffic light system for managing risk.

Some deeper and larger events during the stimulation were located within a zone that had previously been seismically active. So it was inferred that increases in pore pressure were not necessarily the direct trigger, and did not directly control the magnitude of seismic events. Instead, injected water may have changed the physical conditions, including friction coefficient and stress state on the fracture plane, and this is what eventually triggered seismic failure.

Other observations were that the larger events adhered to the constant stress-drop scaling law, but that shear slip was often associated with relatively low critical pore pressure. It was finally concluded that the mechanism for larger events may not be universal, and that there are still significant uncertainties regarding the factors that controlled the magnitude of the micro-seismic events at Basel.

3.7 LANDAU, GERMANY

At Landau, also in the Rhine Graben, two wells were drilled to about 3.3 km depth; one was naturally permeable and the other was stimulated using high pressure injection, so it is a partial EGS project. There were no detected micro-seismic events from the stimulation.

After two years of stable doublet operation, circulating fluids without incident, the project came under review as the result of local seismicity. Two earthquakes (M2.4 and M2.7) were felt by the local population in August 2009, although no significant damage occurred.

Whether the earthquakes were of natural origin or related to operations was not very clear, largely because of uncertainty in hypocenter locations and the absence of any major change in operational conditions at the time. However, after a brief suspension, circulation subsequently resumed at revised operating conditions (lower pressures).

4. PUBLIC REACTIONS TO INDUCED SEISMICITY

Based on reported experiences, both in the scientific literature and in popular media, it is clear that induced seismicity is a community issue, and that it involves a perception of risk. 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 seismic risks. In some instances, however, felt induced seismic events do generate public concern. This is location dependent, but may result from the notion that larger, potentially damaging events could result from future geothermal activities. Because naturally occurring earthquakes are less common in some EGS settings, often far from tectonic plate boundaries, public perception of the risk of large induced seismic events can be a much bigger issue in these quieter geological settings.

Public perception is important and should be dealt with correctly at the start. Expectations and fears should be taken seriously. Prior education about the advantages and potential adverse effects of fracturing is important. An explanation of probable mechanisms is also important, to alleviate concerns that could be miss-placed. For example, it may help to explain that, in most situations, the underlying cause of geothermal induced seismicity is accumulated stress in the ground, which is of natural origin. This stress may be partly released, through seismic failure, and this can be triggered by a relatively small perturbation in fluid pressure. Alternatively, the trigger might be a relatively minor redistribution of thermal and mechanical stresses.

Another point worth noting is that, of the hundreds of developed conventional geothermal systems world-wide, only a small fraction have produced induced seismic events of a magnitude felt by people during normal fluid extraction and injection operations. Furthermore, where they did occur, these events have not significantly curtailed reservoir operations.

5. INDUCED SEISMICITY PROTOCOL

Protocols and review papers for geothermal induced seismicity associated with EGS operations (Majer et al., 2007, 2011) have discussed the key issues. Three of the main conclusions of this work, in terms of dealing with the issues, are as follows:

- Induced seismicity need pose no threat for future development of geothermal resources, so long as sites are selected judiciously, community issues are handled effectively, and operators and licensing authorities understand the potential mechanisms.

- Induced seismicity is generally beneficial for the purposes of monitoring the effectiveness of EGS operations, for providing information on reservoir fluid-flow processes, and for locally relieving accumulated rock stresses.

- Large induced seismic events associated with EGS projects have not caused major damage or injury, however some minor building damage has occurred in an urban setting and insurance claims have subsequently been lodged and settled.

5.1 HAZARD ASSESSMENT

Vibration hazards from geothermal induced seismicity are similar in principle to other underground activities such as mining, hydrocarbon production and brine disposal, CO_2 injection, or dam filling operations, where a possibility exists of triggering seismic stress release if a load changes.

When undertaking a hazard assessment and while considering new geothermal development sites, especially urban locations, it is prudent to consult geological and seismological information to gauge suitability in relation to background natural seismicity, the state of stress, the existence of superficial deposits with potential for exaggerated ground shaking, and the capability of existing buildings and services to withstand seismic shaking.

Criteria used for assessing the relative magnitude of induced seismicity, from the point-of-view of potential effects, should be peak ground velocity and frequency content (rather than peak amplitude which is often used to obtain a local magnitude). The frequencies generated by induced (shallow) events are often too high to cause significant structural damage (typically requiring <10 Hz). Geothermal induced seismicity frequencies, of peak strength at locations close to the hypocenter, are typically in the range of 100-300 Hz; although some larger events (M3-4) can generate significant vibrations at around 40 Hz. Case-by-case assessment of vibration hazard is prudent.

6. SUMMARY OF LESSONS LEARNT

The “traffic-light” approach (Bommer et al., 2006), assures communities 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 ground conditions, proximity of buildings, and susceptibility of infrastructure to vibration damage. This approach is, however, reactive and, in its current form, does not prevent or forecast later triggered events that may be significantly delayed by slow diffusion of pressures or stresses. An improved forward-looking 'traffic-light' protocol, under development through IPGT collaboration (Stefan Weimer, 2012, pers. comm.), will take into account observed trends in seismic behavior from existing datasets, with the intention of providing a probabilistic forecast of the occurrence of larger events in the future.

Some investigations indicate that the smaller the strain energy placed in the formation, the smaller the probability of generating larger seismic events. Pumping at lower pressures over longer periods, or more slowly building up pumping pressures, then slowly reducing pressures, as the stimulation period ends, may be beneficial in terms of reducing the probability of larger seismic events.

Some statistical studies have found that the maximum magnitude of the induced seismicity is limited by the geometry of the volume of the stimulated reservoir (Shapiro et al., 2011), leading to the conclusion that monitoring the spatial growth of seismicity in real time can help constrain the risk of inducing damaging earthquakes.

European experience (Evans et al., 2012) supports the view that injection into crystalline rocks induces more earthquakes than in sedimentary rocks. Crystalline rocks are typically critically stressed and injection into them consistently produces seismic events, but usually of low magnitude.

Experience suggests that the presence of nearby faults does allow transient pressure changes to penetrate further and therefore increases the risk of triggering felt events on existing fractures. However, comparison of case studies does not provide any convincing evidence that deeper injection produces larger magnitude events, and not all major faults are permeable.

Injection at sites with low natural seismicity does not usually result in any felt events, suggesting that low natural seismicity level may be a useful indicator of low induced seismicity risk. However, the converse is not necessarily true.

In conclusion, to assess the risk of large-magnitude induced-seismicity it is important to have good knowledge of the natural background seismicity and the local geology. Mitigation may involve constraining the risk by closely monitoring the spatial growth of a stimulated reservoir.

7. RESEARCH DIRECTIONS

Research into geothermal induced seismicity attributable to down-hole activities, especially those associated with maintaining or enhancing productivity is ongoing. At present, the primary effort is focused on EGS, and the direct effects of high pressure injection, but better understanding of seismicity triggered by conventional operations and thermal transients is also being sought. Through international collaboration, researchers including working groups within the IEA-GIA (Annex 11) and the IPGT (induced seismicity), will target a number of topics. These include the following:

- Discriminate between induced and natural seismic events – identify and characterize attributes of induced events (duration, frequency content, dominant frequency).

- Investigate possible seismic effects during long-term EGS production – including thermo-elastic effects (cooling cracks) and long-term pressure effects.

- Define how far relevant stress field perturbations can extend from EGS operations in terms of safe proximity of stimulated reservoirs to major active faults.

- Characterize post shut-in seismicity after EGS stimulations – mechanisms of delayed micro-seismic events occurring after suspension of injection.

- Design EGS operations to minimize ground shaking – management schemes to adjust volume, temperature or rate of fluid injection; investigate the nature and degree of dependency on the local conditions at depth.

- Undertake lab-scale and full-scale experiments (test-site); investigate rock properties, stress measurements, rock-fluid interaction and mechanisms.

- Produce a refined forward-looking 'traffic light' protocol using seismic probability analysis to assess the risk of larger events.

- Reduce uncertainties – to make forecasting models and probabilistic seismic hazard estimates more reliable.

- Develop methods to improve acceptability, to manage subjective perception issues, to educate stake-holders using credible information and to better communicate probability of extreme events.

- Develop low-cost drilling methods (micro-drilling) for down-hole seismometers to facilitate better resolution and definition of source characteristics and failure mechanisms.

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REFERENCES

Baisch, S., Vörös, R.: Reservoir induced seismicity: Where, when, why and how strong? *Proc. of the World Geothermal Congress 2010*, Bali, Indonesia, Paper 3160, 5p. (2010)

Baria, R., Majer, E., Fehler, M., Toksoz, N., Bromley, C., Teza, D.: International cooperation to address induced seismicity in geothermal systems. *Proc. of the 31st Workshop on Geothermal Reservoir Engineering*, Stanford University, CA, USA, (2006).

Bommer, J., Oates, S., Cepeda, J. M., Lindholm, C., Bird, J., Torres, R., Marroquin, G., Rivas, J.: Control of hazard due to seismicity induced by a hot fractured rock geothermal project, *Engineering Geology*, 83, 287-306. (2006)

Bromley, C.J., Mongillo, M.A.: Geothermal energy from fractured reservoirs – Dealing with induced seismicity. *Open Energy Technology Bulletin*, 48, 7p. http://www.iea.org/impagr/cip/pdf/Issue48Geothermal.pdf (2008).

Cladouhos, T., Petty, S., Foulger, G., Julian, B., Fehler, M.: Injection induced seismicity and geothermal energy. *Geothermal Research Council Transactions*, 34, 1213-1220. (2010)

Evans, K.F., Zappone, A., Kraft, T., Deichmann, N., Moia, F., 2012. A survey of the induced seismic responses to fluid injection in geothermal and CO2 reservoirs in Europe. *Geothermics*, Vol.41, p30-54. (2012)

Ghassemi, A., Tarasovs, S., Cheng A.H.-D.: A 3-D study of the effects of thermo-mechanical loads on fracture slip in enhanced geothermal reservoirs. *International Journal of Rock Mechanics & Mining Sciences*, 44 1132–1148, (2007).

Majer, E.L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B., Asanuma, H.: Induced seismicity associated with Enhanced Geothermal Systems, *Geothermics*, 36, 185-222. (2007).

Majer, E., Baria, R., Stark, M.: Protocol for induced seismicity associated with enhanced geothermal systems. Report of Task D Annex I (9 April 2008), IEA-GIA. http://www.iea-gia.org/documents/ProtocolforInducedSeismicityEGS-GIADoc25Feb09.pdf (2008).

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., Wong, I.: Protocol for addressing induced seismicity associated with enhanced geothermal systems (EGS). http://www1.eere.energy.gov/geothermal/pdfs/egs-is-protocol-final-draft-20110531.pdf. (2011)

McClure, M, Horne, R..: Numerical and analytical modeling of the mechanisms of induced seismicity during fluid injection. *Geothermal Resource Council Transactions*, 34, 381-394, (2010).

Shapiro, S.A., Kruger O.S., Dinske C., Langenbruch C.: Magnitudes of induced earthquakes and geometric scales of fluid-stimulated rock volumes. *Geophysics* 76, Issue 6, WC55; (2011).