Geothermal Induced Seismicity : Summary of International Experience

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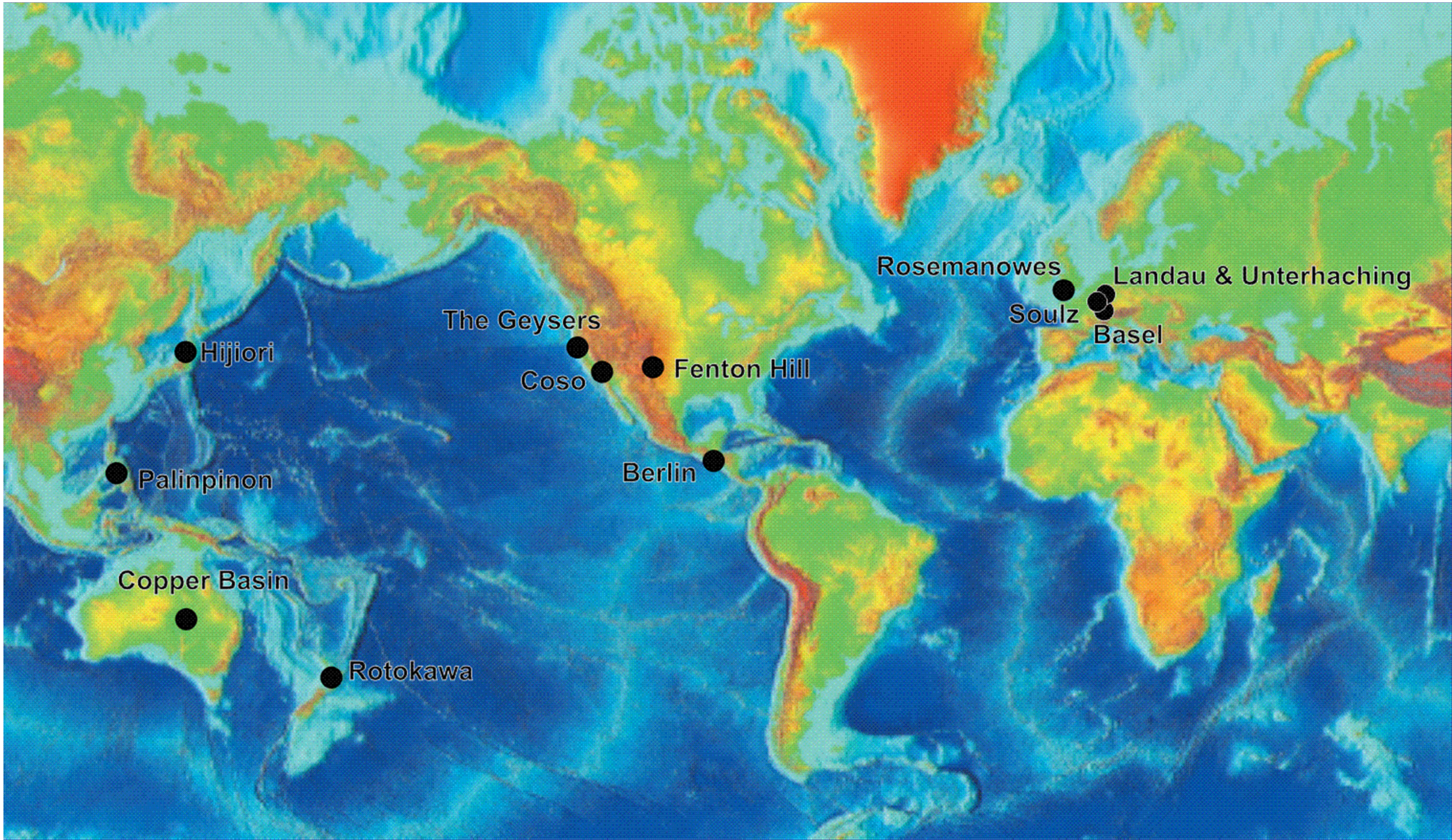
1.0 Background

- 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).
- Associated with conventional projects involving low pressure fluid production and injection, and EGS projects involving high pressure injection stimulation.
- Understanding of the mechanisms has advanced to the stage that models have been developed to simulate the process (Baisch & Voros, 2010, McClure & Horne, 2010).
- Many conventional geothermal fields have been producing for more than 25 years, and the majority have not reported any felt IS. In the few cases that have, IS has generally consisted of small or micro-earthquakes. Maximum magnitude was 4.6 (at The Geysers, California).
- There are no known cases of induced earthquakes in EGS settings from high pressure stimulation or injection causing severe damage (Majer et al., 2005; 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.

1.1 Further background

- Levels of induced seismicity (number & magnitude) depend on natural settings: the local stress & friction, and fault orientations and locations.
- In active tectonic settings, high levels of natural seismicity are common, faults may be pre-stressed, & 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.
- A change in pore pressure may cause asperities (or locked points) on the 'rough' pre-stressed fracture surface to fail.
- Factors affecting seismicity 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.

- Primary benefit of Induced Seismicity is increasing permeability (injectivity).
- Controllable factors are : injection pressure & temperature, volume, duration, & ramping rates. But, uncertainties, & variability between geological settings, make it difficult to establish reliable correlations between the level of seismicity and any of these factors that could be consistently applied to new settings.

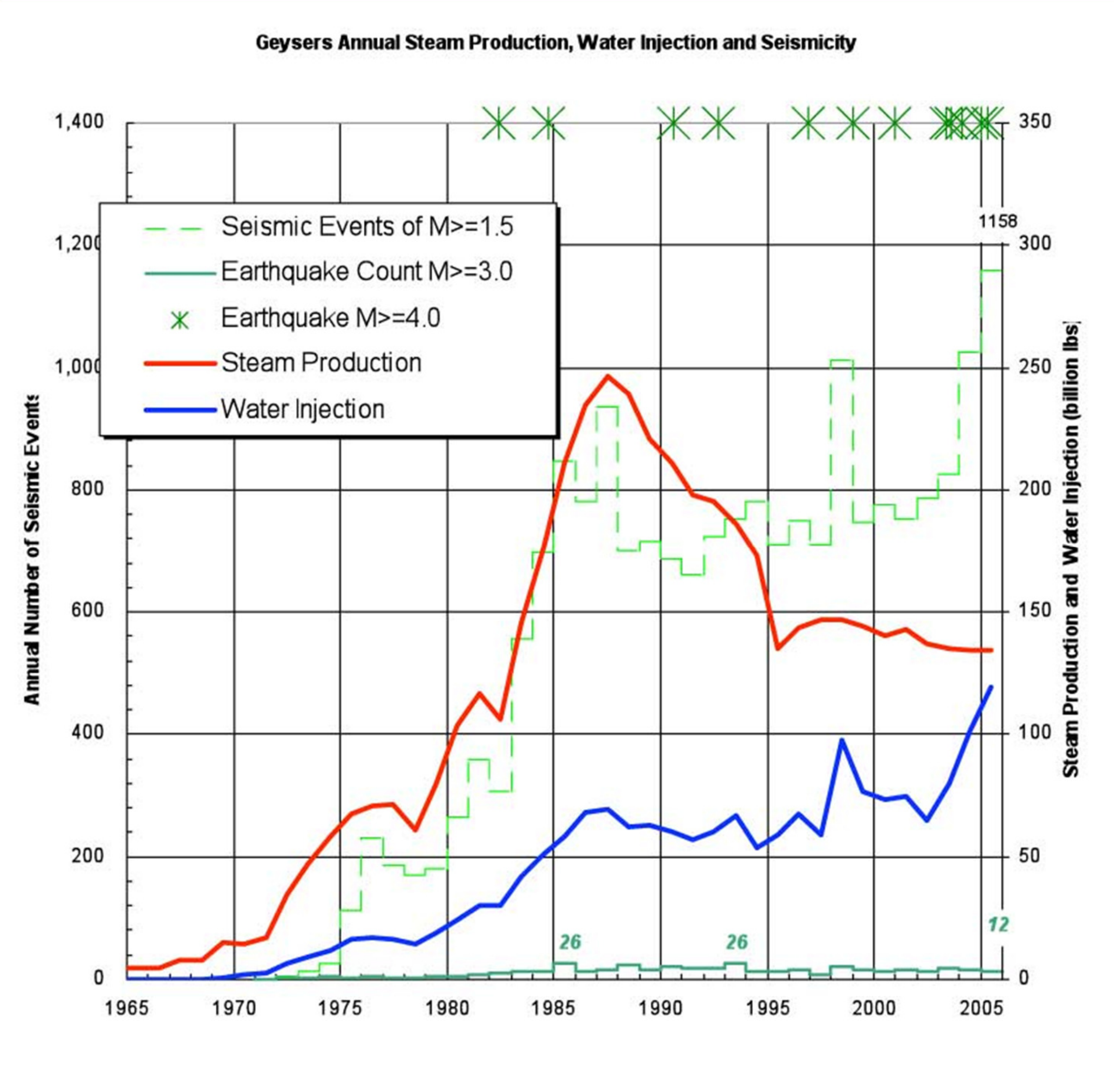


Map of sites of geothermal induced seismicity case studies

2.0 KNOWLEDGE GAINED FROM CONVENTIONAL PROJECTS

2.1 The Geysers, California, USA

- Approximately 1000 seismic events are located per year (M>1.5). On average,~1/year has been of magnitude M>4 (maximum 4.6).
- Triggering of micro-earthquakes by large regional earthquakes is observed.
- Reservoir steam pressure has been in decline since production started, but seismicity was located throughout production zones, so a simple mechanism of hydraulic shear failure due to pore pressure increase is not favoured.
- Rates of seismicity are correlated with steam extraction & increasing injection rates of cool water, initially surplus steam condensates, but in 1997 and 2003 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).
- 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.
- Approximate correlation observed between annual injection volume & 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.



The Geysers 1965-2006 annual steam production (red), water injection (blue), seismic event count (green, stars >M4) (Majer, LBNL)

The Geysers : Mechanisms

- Diverse set of mechanisms influence seismicity. 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 over 20 years).
- Mechanism for deep seismicity is 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 recent 'donut' region of low seismic density surrounded by higher seismic density appeared in high temperature zone underlying NW reservoir, an area of high volume injection. Local de-coupling between injection and induced seismicity may reflect accumulation of injectate as plumes in 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 causes of induced seismicity at The Geysers.

2.2 Coso, California, USA

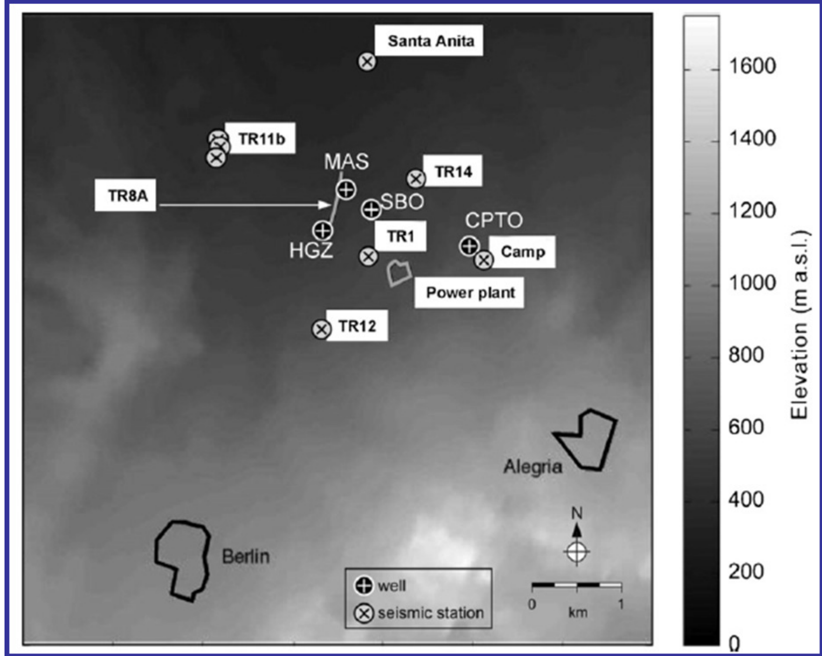
- At Coso, a direct correlation between the locations of micro-seismicity and the injection and circulation of geothermal fluid was observed along with an observed spatial, though not temporal, correlation with natural seismicity extending southeast of the field. Areas of high seismicity are interpreted to indicate pre-existing fracture zones and dominant flow paths, and also infer different stress patterns within the field.

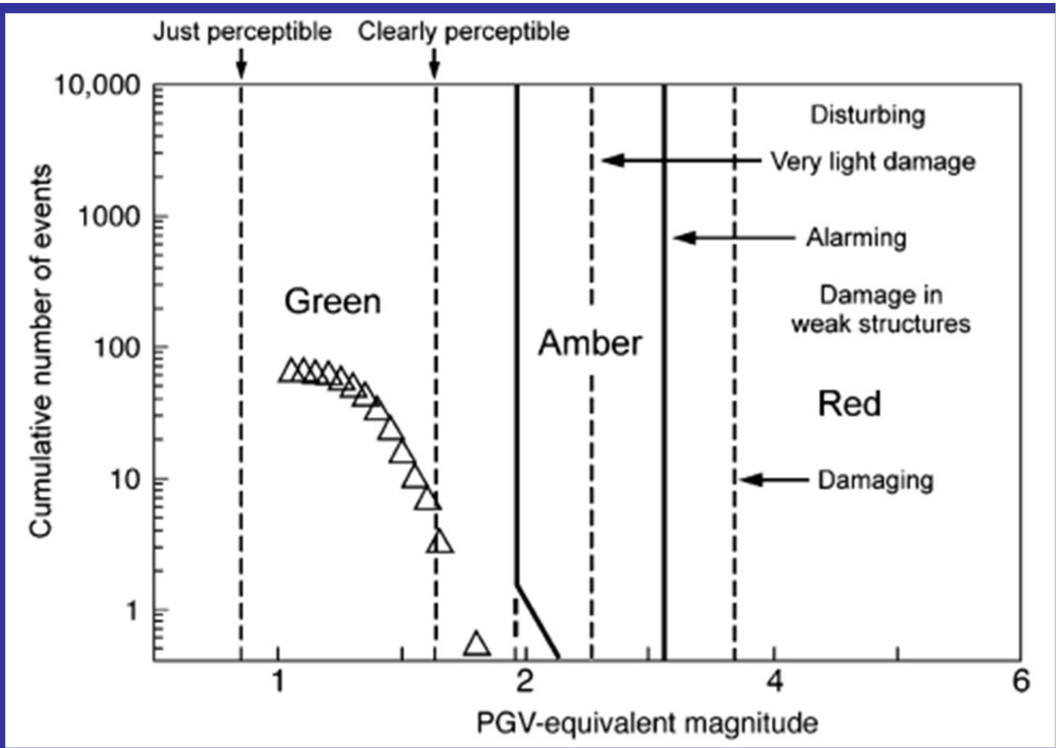
- Modelling suggested that there is a trans-pressional (strike-slip and oblique compression) regime on the periphery of the field, whereas the geothermal area is characterised by a trans-tensional (strike-slip and oblique extension) regime. The stress regime observations are consistent with the focal mechanisms, and the explanation that different stress patterns are associated with fault-bounded geological blocks.

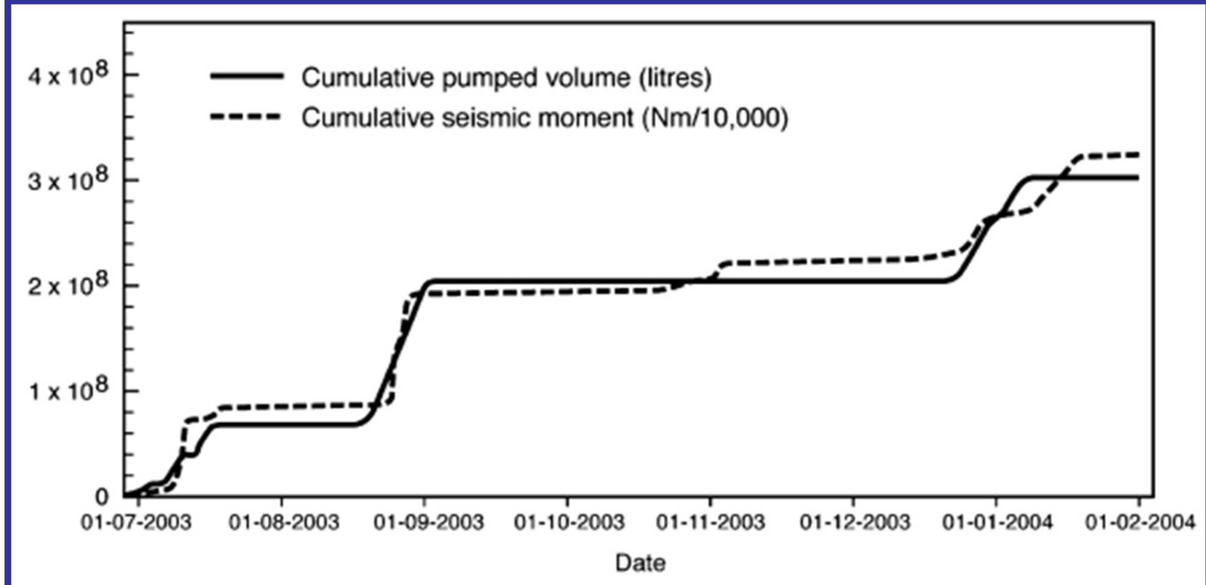
- Thermal stresses appear to play an important part in explaining induced seismicity, in particular an observed delay between injection and seismicity.

2.3 Berlin, El Salvador

- As Berlín is located in a naturally seismically active region, it is difficult to differentiate between natural and induced or triggered seismic events.
- Some micro-seismicity is spatially correlated to areas of pressure and temperature change, in both production and injection areas.
- No clear correlation in timing was found between the monthly seismicity data and the mass injected or extracted, although there is a spatial correlation with the geothermal anomaly.
- Seismicity in the reservoir increased after the occurrence of two large nearby tectonic earthquakes in early 2001.
- A calibrated real-time 'traffic-light' control system was put in place in 2003 to limit injection stimulation operations if the levels of vibration (peak ground velocity) from injection-induced seismicity exceeded acceptable levels, taking into account the stability of local rural housing and shallow ground conditions. The thresholds were not exceeded, and the project was not adversely affected.
- Fractures within the 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.
- Events are triggered by stress changes associated with external sources such as large regional earthquakes as well as by reservoir changes.



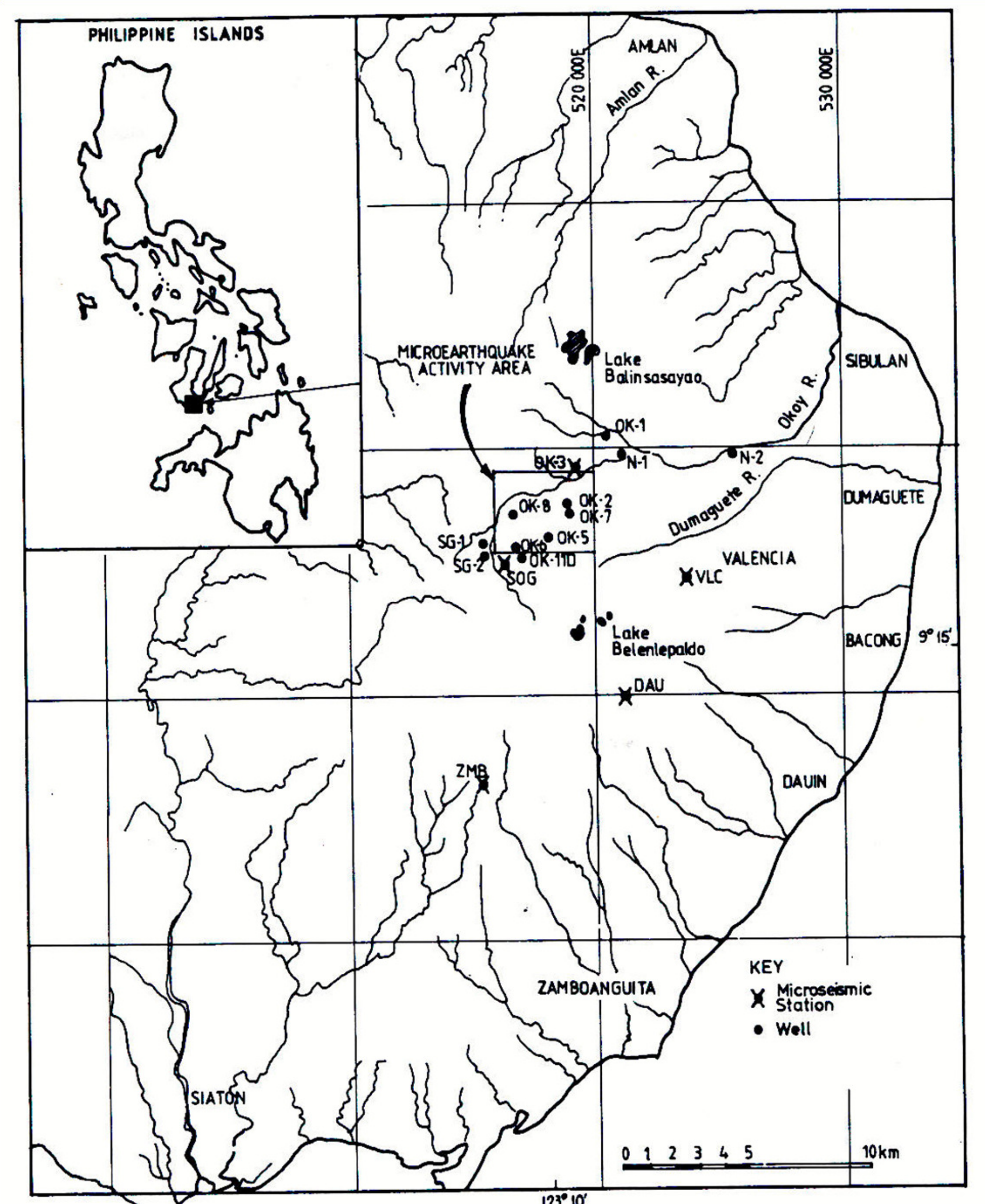


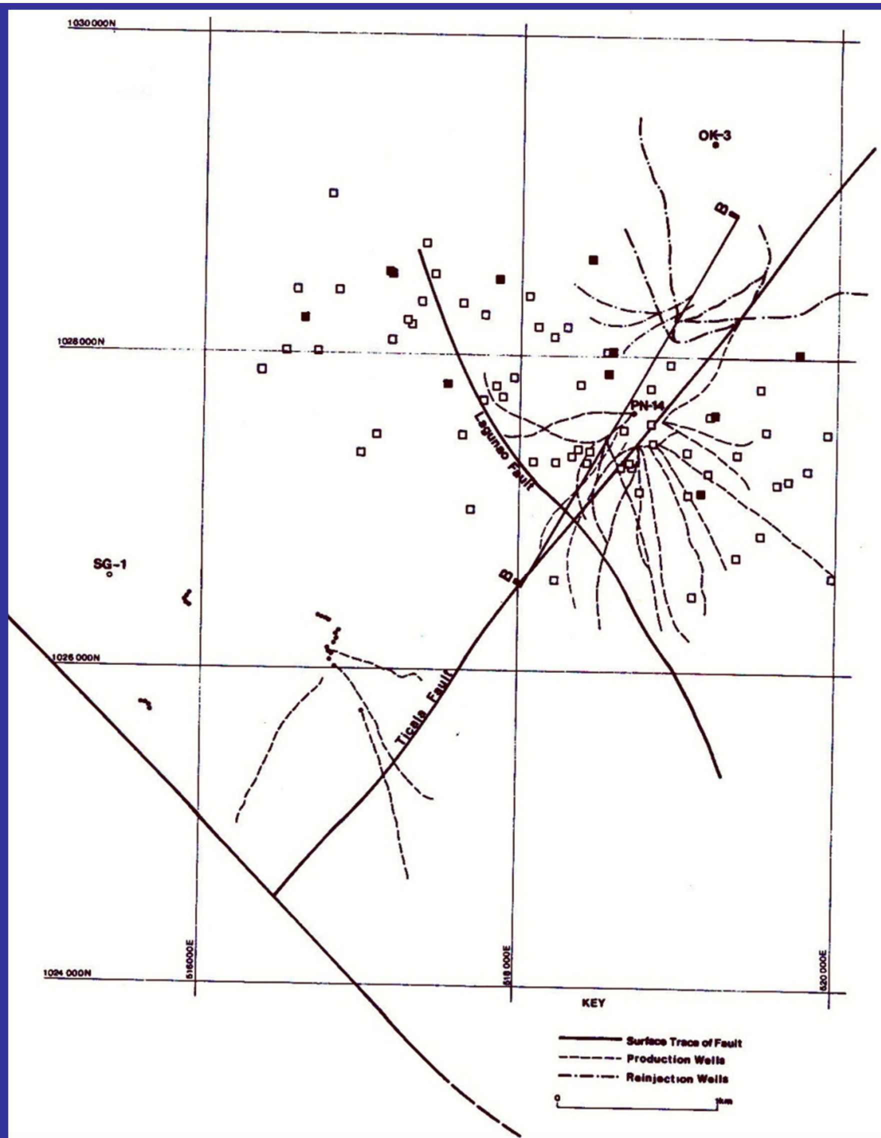


Berlin, El Salvador TR8A Injection stimulated seismicity (Bommer, 2006)

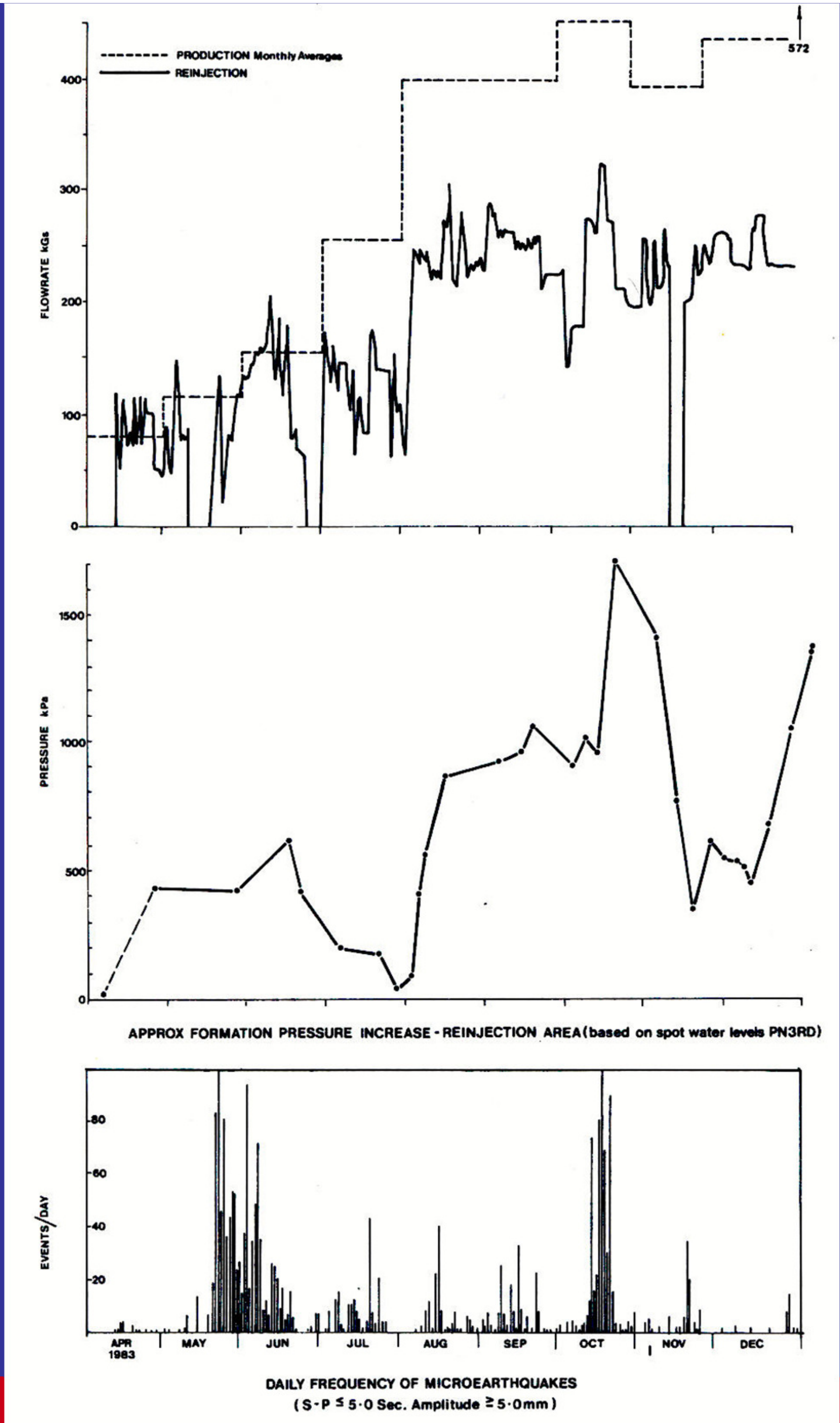
2.4 Palinpinon and Tongonan, Philippines

- 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 (0<M<2.5). Some were felt within the project due to their shallow depth (1-4 km) and proximity.
- There was a 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, and were not 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 development doubled in capacity.
- In 2007, a M-5 earthquake of tectonic origin (triggered by 70 km deep event a minute earlier) occurred at shallow depth within the borefield and 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.





Palinpinon event locations , major faults and well tracks (Bromley et al 1987)



Palinpinon, Philippines:

Correlations between micro-earthquake daily rates (0-100), formation pressure in reinjection sector, and production and reinjection flowrates (during 1983).

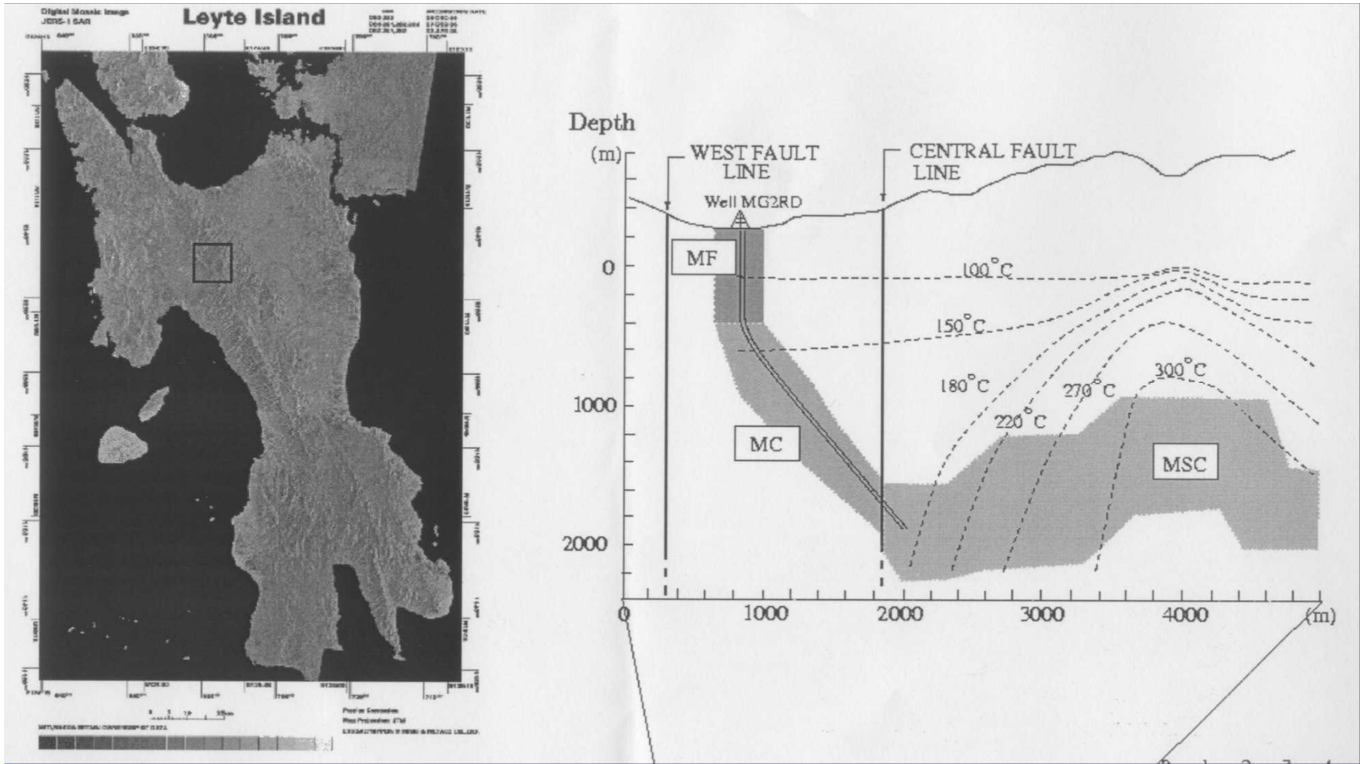
Max 2.4 (felt)

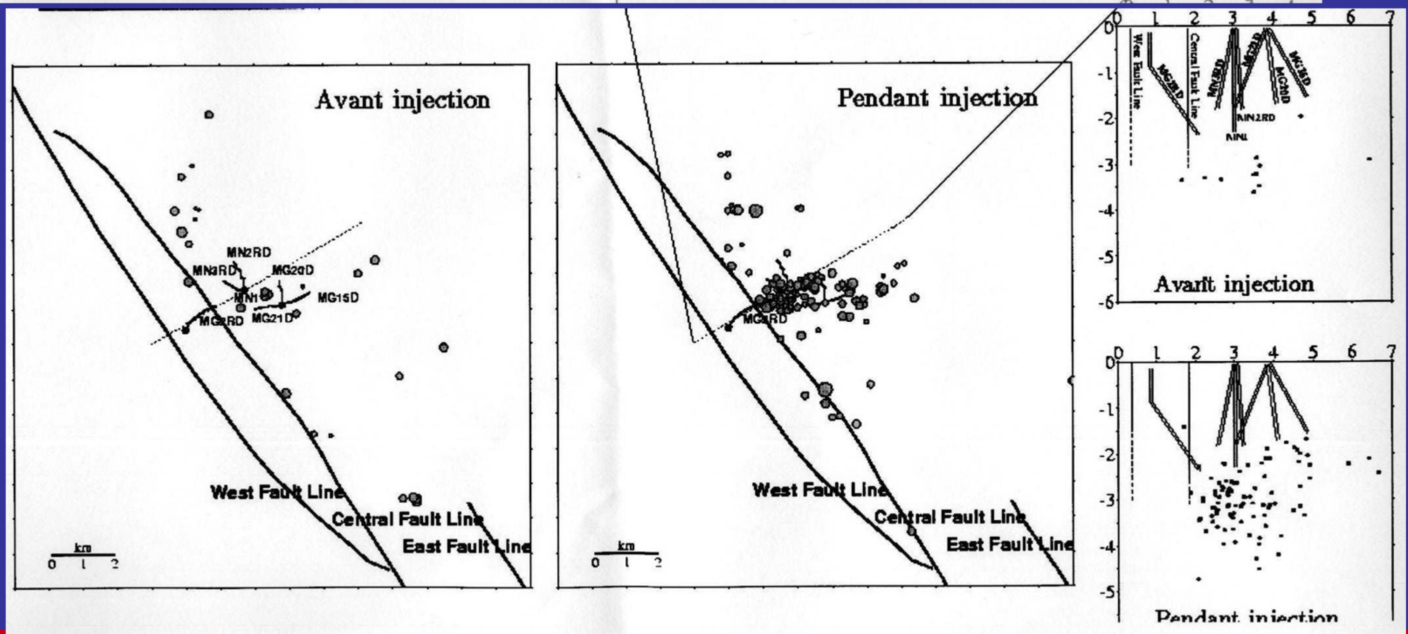
Fault plane solns-normal or strike-slip

3 days time delay

B slope = 1.1-1.3

Shear failure





Tongonan (Leyte, Philippines) Seismicity induced during 1997 high pressure cold hydraulic stimulation of MG2RD; M<2

(Dorbath et al)

2.5 Other Geothermal Fields

- Seismicity occurred during deep injection at Svartsengi Geothermal Field, Iceland, and, in 2011, at the Hellisheidi geothermal field in the Hengill Volcanic area of Iceland.

- Induced seismicity (maximum M-3), has been recorded at Larderello-Travale steam-dominated geothermal field in Italy in response to steam condensate reinjection, and in three other Italian geothermal areas in response to injection.

- In Olkaria Geothermal Field, Kenya, induced seismicity (maximum M 1.5) was correlated to discharges from a production well in 1997.

3.0 KNOWLEDGE GAINED FROM EGS PROJECTS

- EGS fracturing experiments can involve small volumes of high pressure injection to induce rock failure, or larger volumes of fluid at lower pressure, and longer-term circulation tests. Seismicity is triggered by fluid flow, through changes in pore pressure on fractures, or through transient thermal stresses associated with cooler fluids.
- During reservoir stimulation, hydraulically-induced tensile rock failure may occur when the fluid pressure exceeds the rock fracture gradient. However, shear failure is more often observed, and at much lower fluid pressures, due to triggered seismic release of pre-stressed fractures.
- The increased pore pressure or thermal contraction can release asperities on fracture surfaces, thereby facilitating shear failure and stress release.
- These triggered events, similar to natural earthquakes, have moment magnitudes more dependent on the magnitude of local stress release and fracture surface area than on the amount of fluid pressure increase.
- The maintenance of EGS reservoir permeability during long-term circulation may be enhanced by triggered seismicity that continues throughout the project lifetime. The mechanism is gradual stress changes associated with slow cooling, and pressure diffusion into low permeability reservoir rock.

3.1 Fenton Hill, New Mexico, USA

- The majority of the observed seismicity (~8000 events, 1983) at Fenton Hill 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 also occurred in close proximity to tensile events, and at locations where fluid pressure is assumed to be sufficient to trigger shear failure, but insufficient for tensile failure.

- Seismicity was found to occur along pre-existing fracture surfaces that are favourably oriented with respect to the *in situ* stress-field. This allows shear slip. The fracture plane with the highest ratio of shear to normal stress acting along it is the one most likely to slip, and events occur when the normal stress on such a fracture plane is sufficiently reduced by an increase in pore fluid pressure.

3.2 Rosemanowes, Cornwall, U.K.

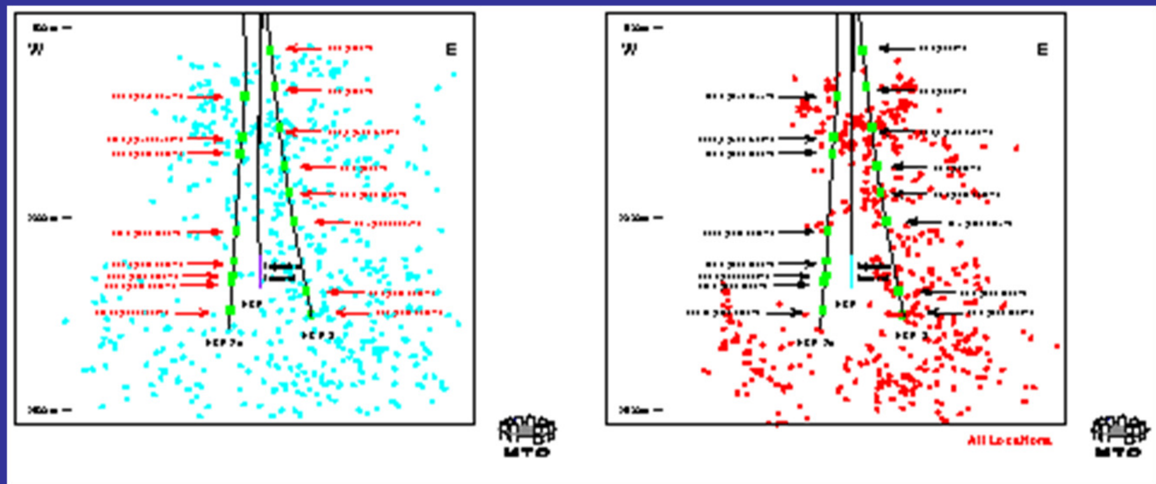
- High pressure **fracture stimulation** was followed by **fluid circulation** at 2.2 km depth in granite. During the first injection phase, MEQ were observed at low flow rates and wellhead pressures of 3.1 MPa. During the second injection phase (up to 14 MPa) a **downward migration** of MEQ locations was observed although seismic activity was less intense, implying **stresses** had already been **reduced**. MEQ activity defined 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 (**1.9**) was less than the predicted maximum magnitude of 3.5, which was 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.

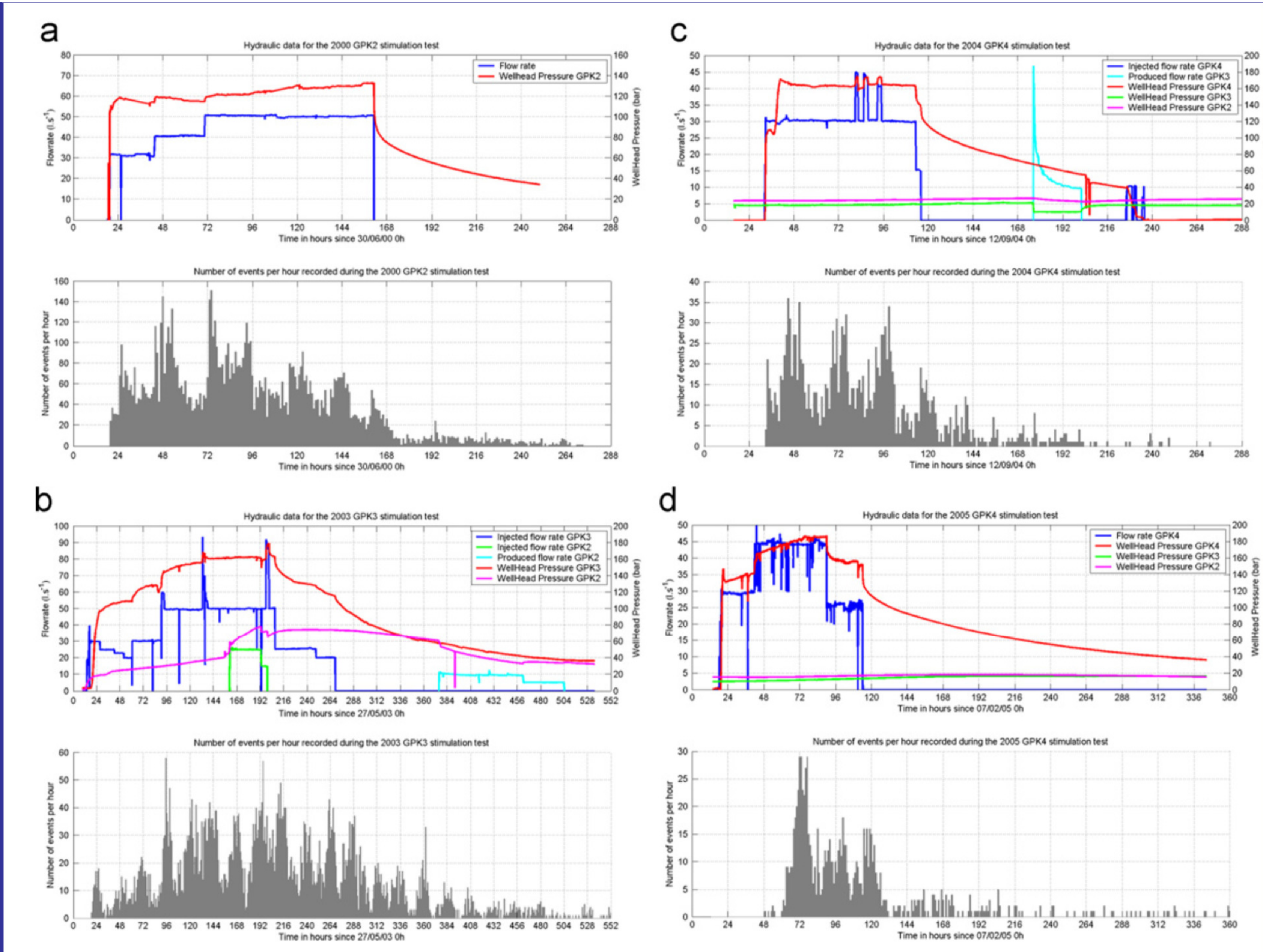
- The induced seismicity is caused by **shear failure** as the result of slip on joints. This occurs when the effective stress is reduced by increasing the pore fluid pressure. The spatial orientation of the induced seismicity was coplanar with the caldera ring fault structure, suggesting a **pre-existing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

Hijiori Test Field of Hot Dry Rock Project (NEDO) in Okura-mura, Yamagata Prefecture



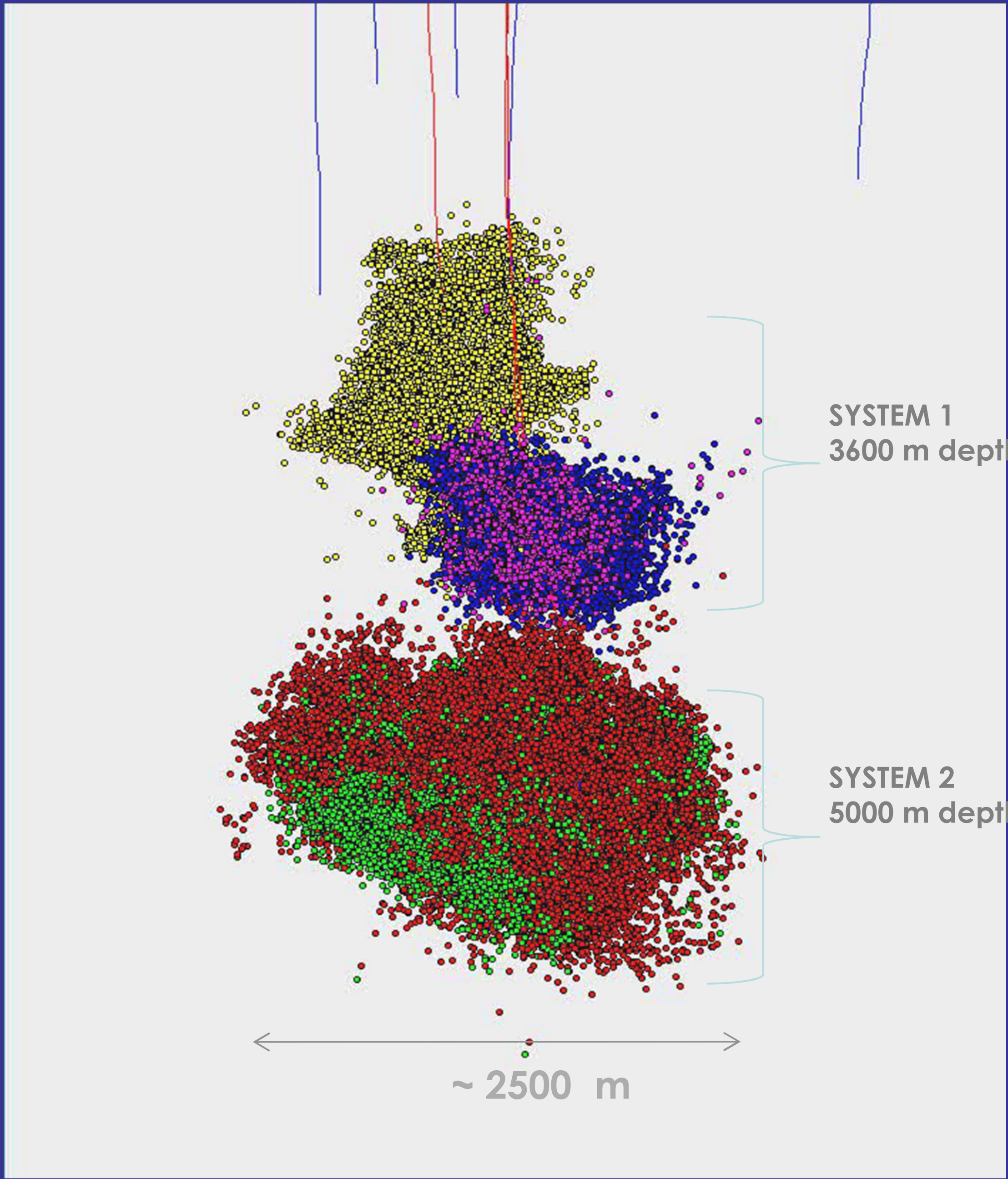
3.4 Soultz, France

- 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 4.5 to 5 km depth, and then fluid circulation. The largest events were M 1.9 during the initial stimulation and M 2.9 during deeper stimulation. Although no structural damage was caused, public complaints led to restrictions on subsequent stimulation options.
- Injection stimulation of well GPK1 induced fracturing at differential pressures of up to 7.5 MPa. MEQ started 17 hours after injection commenced, and produced a sub-vertical 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 M_L=2.9) to occur several days after the stimulation ended. This illustrates the limitations of a ‘traffic light’ protocol when applied to injection activities for risk management.
- Stimulation of GPK4 at 30 to 45 l/s and 14-18 MPa (22 kT), triggered events up to M_L 2.7 after the 1st day. 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 clusters (swarms).



Soultz : a. GPK2 2000, b. GPK3 2003, c. GPK4 2004, d. 2005

From Dorbath 2009



Soultz :
Sequence of Induced seismicity clouds with depth and time 1993-2003

From Roy Baria EGS Energy Ltd

Soultz Observations

- Subsequent fluid circulation tests undertaken between Soultz wells resulted in several hundred locatable MEQ of up to M 2.3. 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 IS can occur under a broad range of operational conditions.

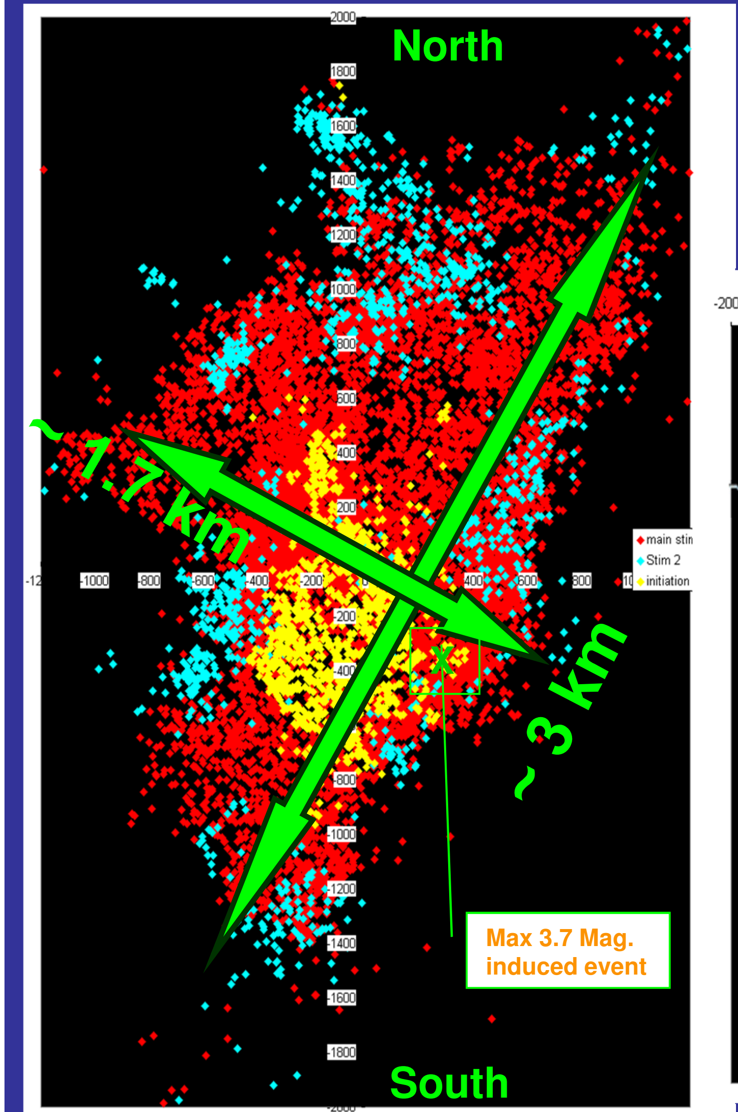
- Some MEQ events were generated by seismic slip on sub-vertical, hydrothermally-altered, cataclastic shear zones. These zones contain numerous limited-scale fractures with evidence of past movement from slickensides. They are optimally oriented for strike-slip shear failure in the prevailing stress field.

- A downward progression of the induced seismicity with time was observed. Permeability was initially relatively low. IS created a self-propped high-permeability flow path, opening up vertical pathways, and facilitating downward penetration of fluids and further micro-seismicity. The MEQ distribution indicates fluid penetration along existing structures with enhanced permeability.

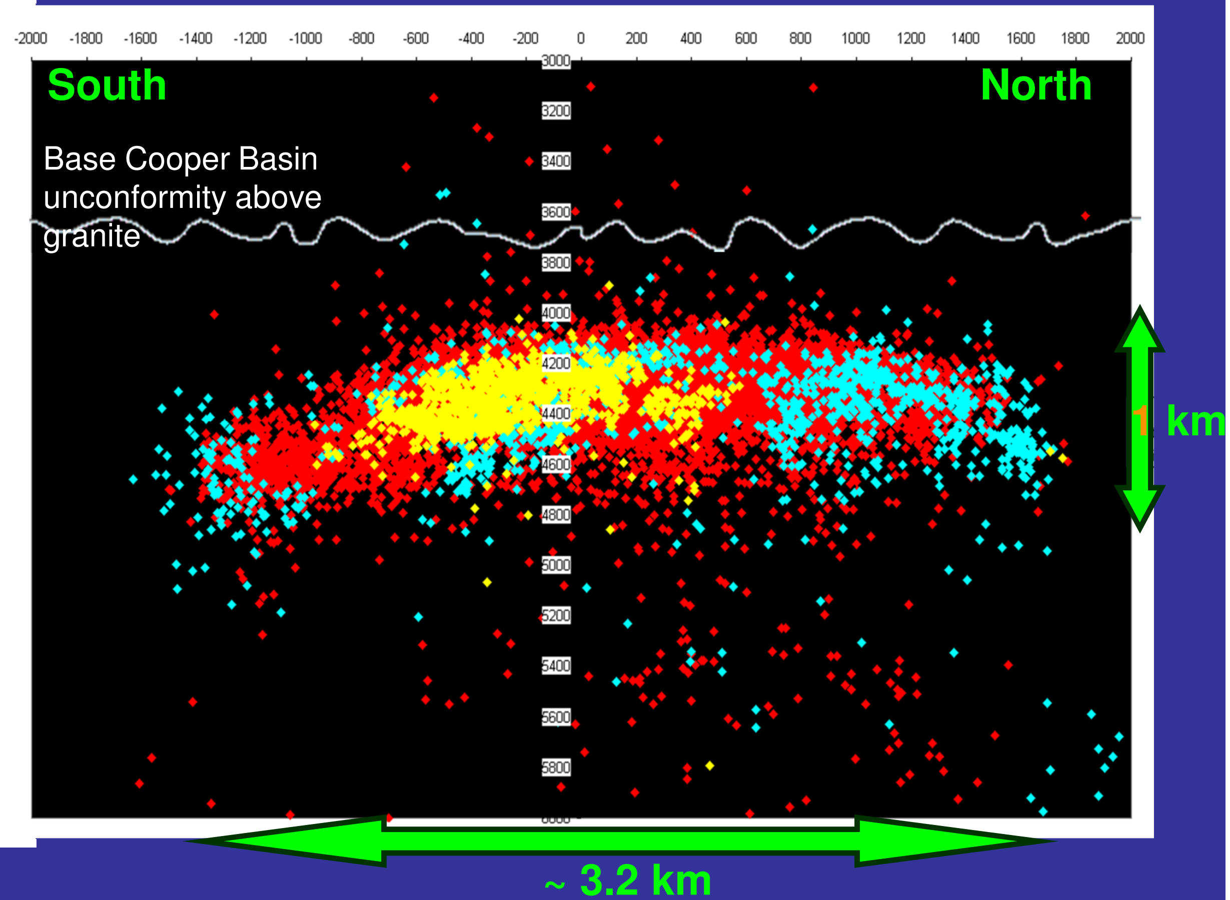
3.5 Cooper Basin, Australia

- Granite basement at ~3.6 to 4.6 km depth; stress regime is over-thrust; minimum stress direction mostly vertical; induced fracture planes horizontal (some vertical).
- Maximum temperature 264°C ; pumped stimulation mixed success (up to 25 l/s at 210°C); HB1: MEQ Mag. up to 3.7, within 0.6 km^3 horizontal zone; excess artesian pressure 35 MPa; no surface damage reported; remote location : little community concern; seismicity migrated away from the injection well with time.
- Previously activated regions became seismically quiet (Kaiser effect) : stress relaxation processes. I S from repeat stimulation was not detected until a day after the start of injection, and started at the outer boundary of the previously activated zone, following the same sub-horizontal structure.
- I S from fluid overpressure relative to the local stress state; generated by slip, or failure of asperities along existing fractures; no direct relationship between the magnitude of the events and the injection records 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. The larger events possibly break a hydraulic barrier, allowing extension of the seismic event 'cloud' into previously quiet zones.

- Initial phase stimulation, P-wave arrivals – Habanero
- Main phase stimulation, P-wave arrivals – Habanero
- Last phase stimulation, P-wave arrivals – Habanero



Plan View: Habanero, Cooper Basin



Cross – Section View

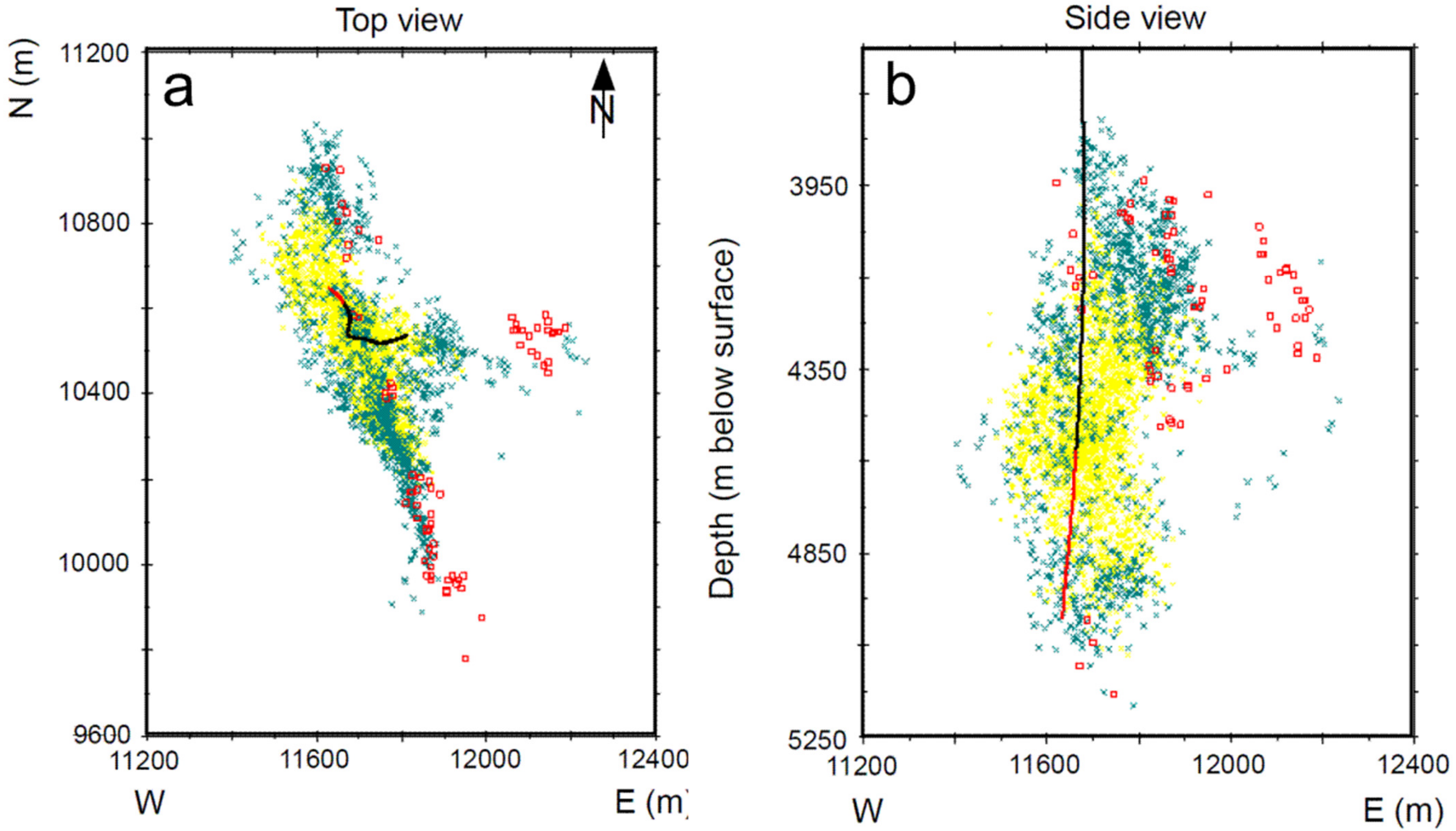
Courtesy of Doone Wyborne
Geodynamics

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 stimulation (up to 50 l/s, at 30 MPa WHP) resulted in several felt events (up to M_L 2.6). Consequently, following a "traffic-light" protocol, pumping was stopped. Events of M_L 2.7 and 3.4 occurred in the subsequent 24 hours. Well head pressures were later reduced by bleeding off. After a detailed seismic risk study, 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, a third of the injected water flowed back. This resulted in decreased rates of seismicity. However, sporadic MEQ activity, (M_L up to 3.2), 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 occurred in response to slow pressure diffusion or temperature changes. These experiences reduce the viability and effectiveness of a simple traffic light system for managing risk.



Locations of seismic events from the Basel experiment. Timing indicated by colours: yellow show events during the active injection phase from 2-8 December 2006, green events from the early post-stimulation phase from 8 December 2006 – 2 May 2007, and red events during the later post-stimulation phase from 3 May 2007 – 30 April 2009. The black and red line show the well location (cased and open). (Ladner and Häring, 2009).

Basel Observations

- Some deeper & larger events during the stimulation were located within a zone that had previously been seismically active. So 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 triggered seismic failure.

- The larger events adhered to the constant stress-drop scaling law. Shear slip was associated with relatively low critical pore pressure.

- There are still uncertainties regarding the factors that controlled the magnitude of the micro-seismic events at Basel. The mechanism for large events may not be universal.

3.8 Landau, Germany

- At Landau, in the Rhine Graben, 2 wells were drilled to about 3.3 km depth; one was naturally permeable and the other was stimulated using high pressure injection. There were no detected micro-seismic events from the stimulation.

- After 2 years of stable doublet operation, circulating fluids without incident, the project came under review as the result of local seismicity. Two earthquakes (M_L=2.4 and 2.7) 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 initially disputed, largely because of uncertainty in hypocentre locations and the absence of any major change in operational conditions at the time.

- Operation subsequently resumed at revised operating conditions (lower pressures).

4.0 PUBLIC REACTIONS TO INDUCED SEISMICITY

- Induced seismicity is a community issue, involving perception of risk.
- Explanation of probable mechanisms is important (eg. accumulated stress of tectonic origin is relieved or triggered by relatively small perturbations in pressure, or by redistribution of thermal and mechanical stresses).
- Experience shows that induced seismic events at geothermal projects are generally small in magnitude. However, because of their shallow origin, larger events can sometimes be felt at the surface.
- In some instances, induced seismic events generate public concern. This may result from the notion that larger, potentially damaging events could result from future geothermal activities.
- However, there have been no instances of significant damage from induced events, so the possibility of increased ground-shaking is not usually a public concern, unless it is fed by media hype.

- 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.

- Of the hundreds of developed conventional geothermal reservoirs world-wide, only a few have produced induced seismic events of a magnitude felt by people during normal fluid extraction and injection. These events have not curtailed reservoir operations.

- 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.

5.0 INDUCED SEISMICITY PROTOCOL AND MITIGATION :

- Published protocols and review papers for I S associated with EGS (Majer et al, 2007, 2008, 2011) have identified the key issues, and conclude that:

- I S 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.

- I S 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 caused no major damage or injury to date; however minor damage claims have been settled.

- 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.

5.1 Hazard Assessment

- EGS induced vibration hazards are similar 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 considering 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 magnitude of induced seismicity should be ground acceleration (or velocity) and frequency content. The frequencies generated by induced (shallow) events are generally too high to cause significant structural damage (requiring <10 Hz). Geothermal induced seismicity frequencies are typically 100-300Hz; although some larger events (M3-4) generate waves at around 40Hz. Case-by-case assessment of vibration hazard is prudent.

- 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 reactive and does not prevent later triggered events that are significantly delayed by slow diffusion of pressures or stresses.
- An improved traffic light protocol , under development, will take into account observed trends in seismic behaviour 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.
- 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 in 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.

- The presence of nearby faults allows pressures to penetrate further and increases the risk of triggering felt events on existing fractures.
- Deeper injection does not necessarily produce larger magnitude events.
- Injection at sites with low natural seismicity typically does not result in any felt events, suggesting that low natural seismicity level may be a useful indicator of low induced seismicity risk. The converse is not necessarily true, however.

- 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 involves constraining the risk by closely monitoring the spatial growth of a stimulated reservoir.

6.0 ONGOING INDUCED SEISMICITY RESEARCH

- **Discriminate between induced and natural seismic events –** identify and characterise attributes (if any) of induced events (duration, frequency content, moment tensor).
- **Investigate seismic effects during long-term operation (production phase) –** including thermo-elastic effects (cooling cracks) and long-term pressure effects.
- **Define how far relevant stress field perturbations can extend from EGS operations –** implications in terms of safe proximity of stimulated EGS 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 downhole EGS operations to minimize ground shaking –** management schemes involving adjustment of volume, rate or temperature of fluid injection.
- **Develop alternative hazard assessment techniques -** e.g. extreme event based assessments; Probabalistic Seismic Hazard Assessment (PSHA) framework; improved traffic light protocol.