Injection-induced seismicity: lessons learned and open questions

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Induced (or triggered) seismicity is nothing new

Induced seismicity is a recognised risk in any Earth-engineering endeavour that changes the stress state or pore pressure of a rock mass

- Reservoir impoundment
- Mining and tunnelling
- Fluid waste disposal through injection
- Oil and gas production
- Quarrying
- Enhanced Geothermal System (EGS) development
- Hydrothermal exploitation

Largest event magnitudes from non-EGS induced seismicity

Fluid extraction
Lacq gas reservoir, SW France: M_L = 4.0
Gas reservoirs in the Netherlands: M_L = 3.5

Reservoir impoundment
Koyna (1982): M_L = 6.3
Killari (1993): M_L = 6.1
Aswan (1981): M_L = 5.6

Mining activities
South African gold mines: M_L = 4.0
Mines in the Ruhr region, Germany: M_L = 3.0

Long-term fluid injection into:
Basement at 3.7 km at Rocky Mountain Arsenal (Denver): M_L= 4.0
(M_L=5.5 1 yr after stop)
Fault in limestone at 4.55 km at Paradox Valley Colorado: M_L = 4.3
(after 4 yrs injection)
Sandstone above basement at 1.7 km in Ashtabula-NY: M_L= 3.8
(M_L=4.2 14 yrs after stop)

Deep geothermal systems and seismicity

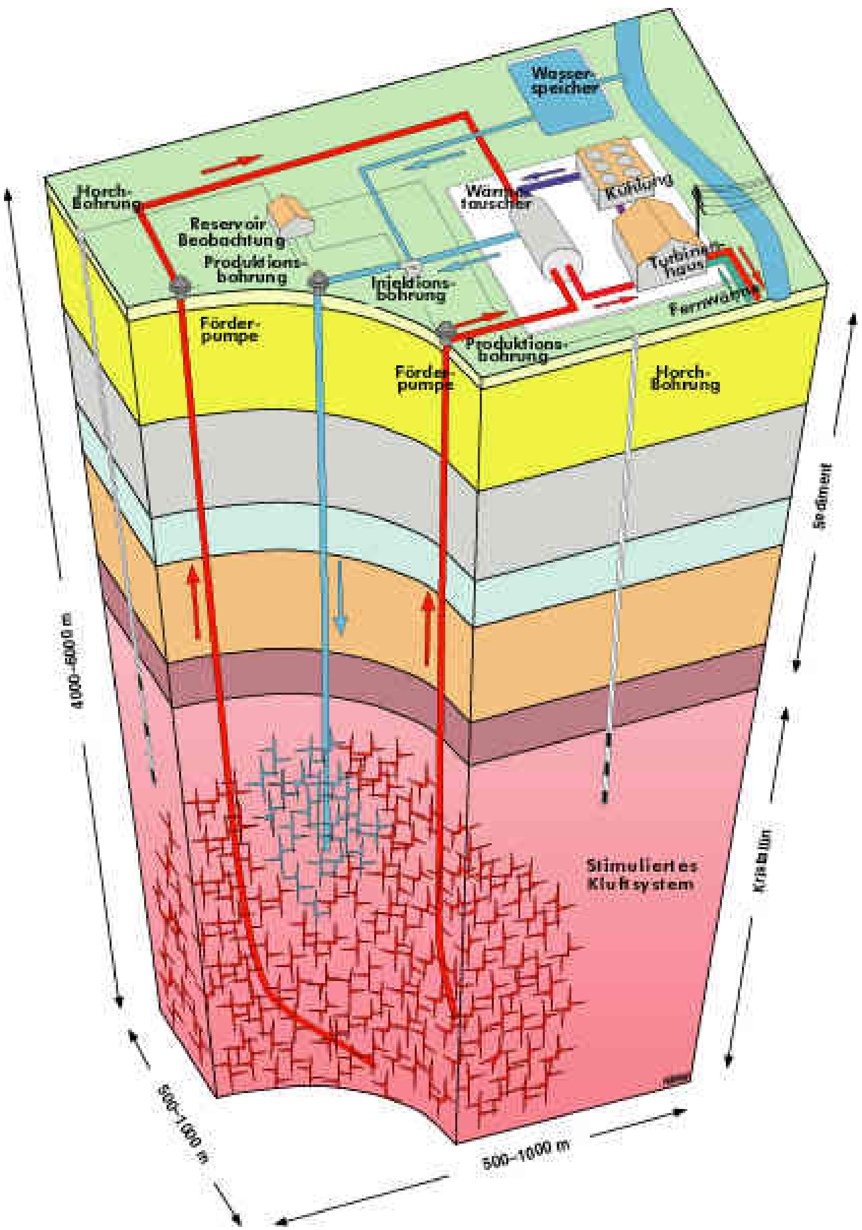
Heat extraction at depths of 1-5 km by water circulation

"Passive" (hydrothermal)
Exploit existing aquifers

"Aktive" (EGS or HDR)
Permeability needs to be enhanced by massive stimulation

"Induced" seismicity

"Triggered" seismicity

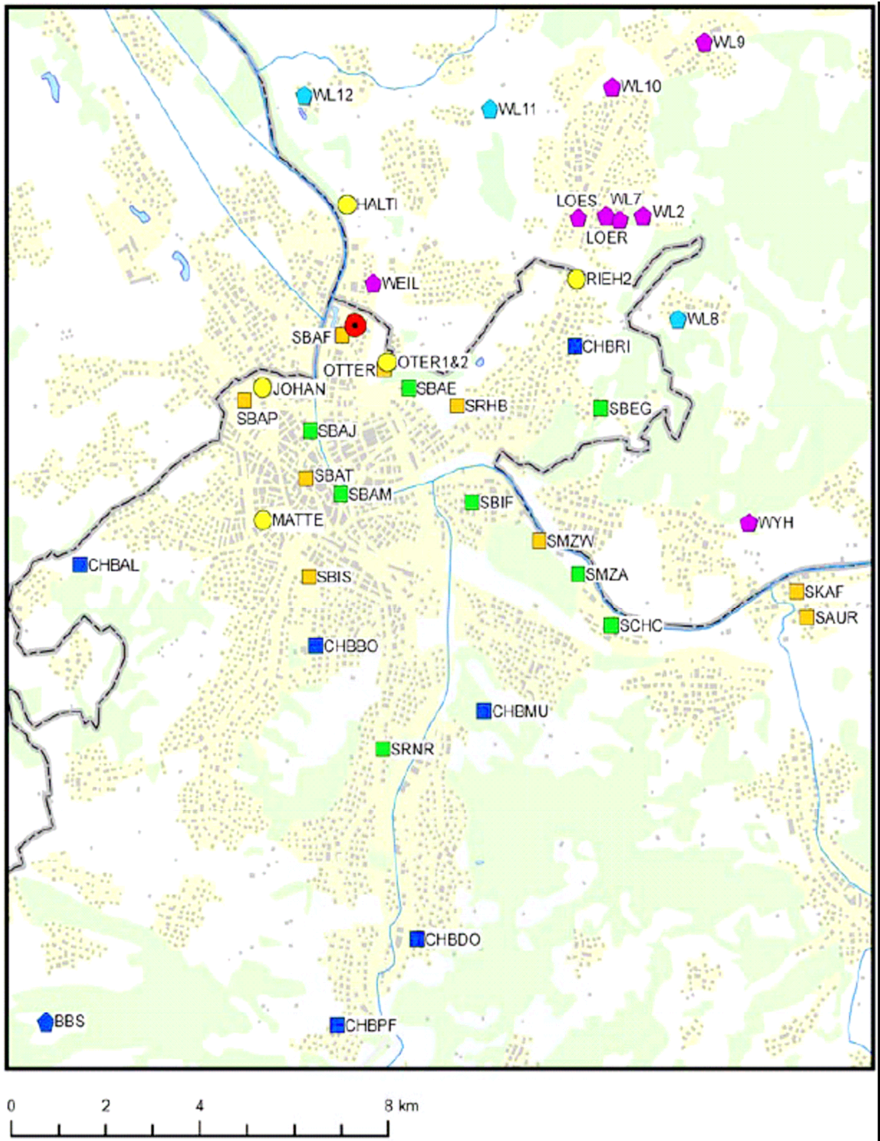


The Basel EGS project

Geothermal heat and power for
5000 households:
3 MW electric
20 MW thermal

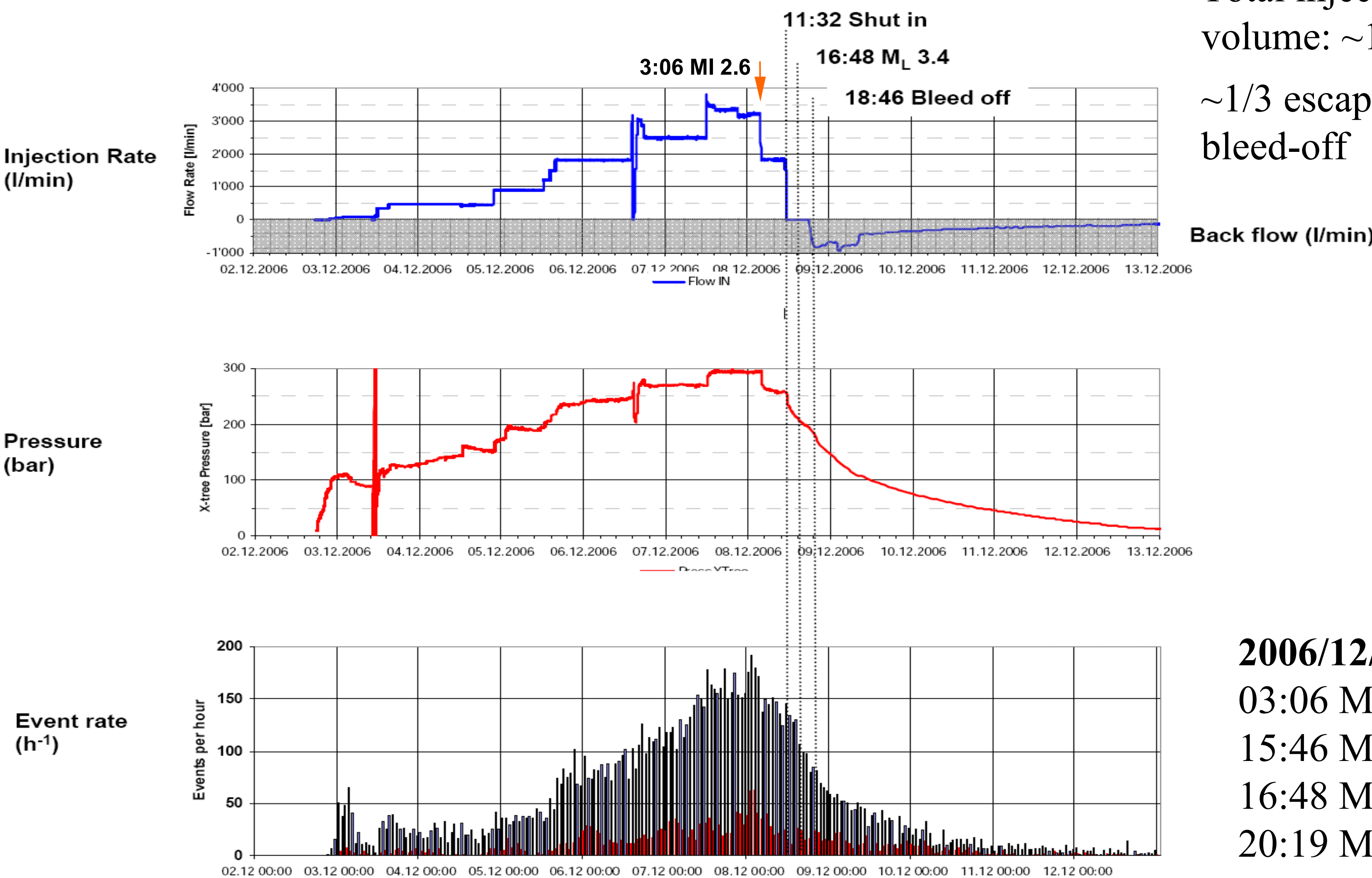
From a 200 deg C reservoir to be created at a depth of 5 km

(Geothermal Explorers Ltd., 2004)



Legend

- Borehole
- Borehole sensors Geothermal Explorers
- Online accelerometers SED
- Offline temporary accelerometers SED
- Offline permanent accelerometers SED
- High-gain seismometer-network LED
- High-gain temporary seismometers LED
- Accelerometers LED

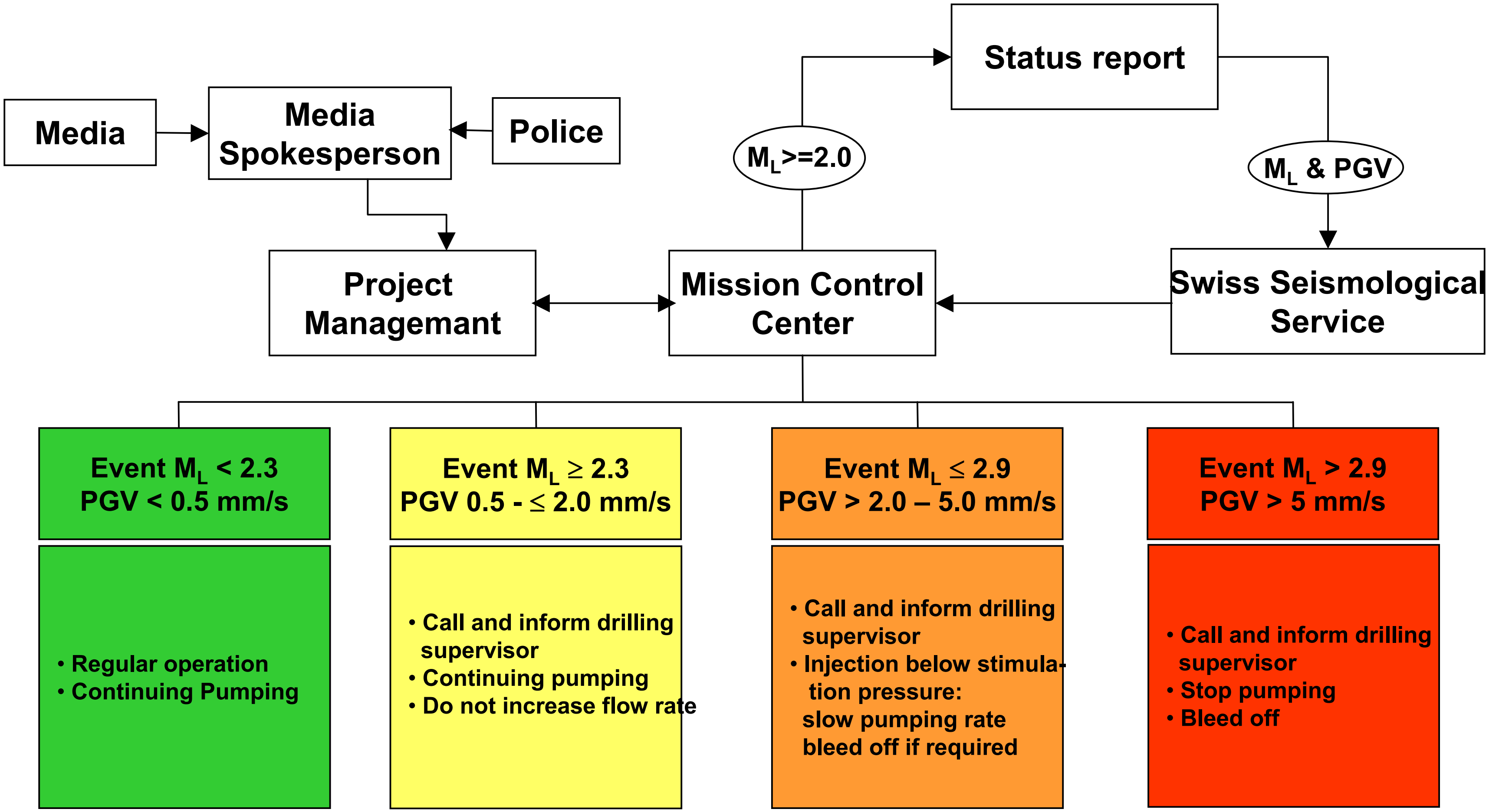


Total injected volume: ~11'500 m3

~1/3 escaped after bleed-off

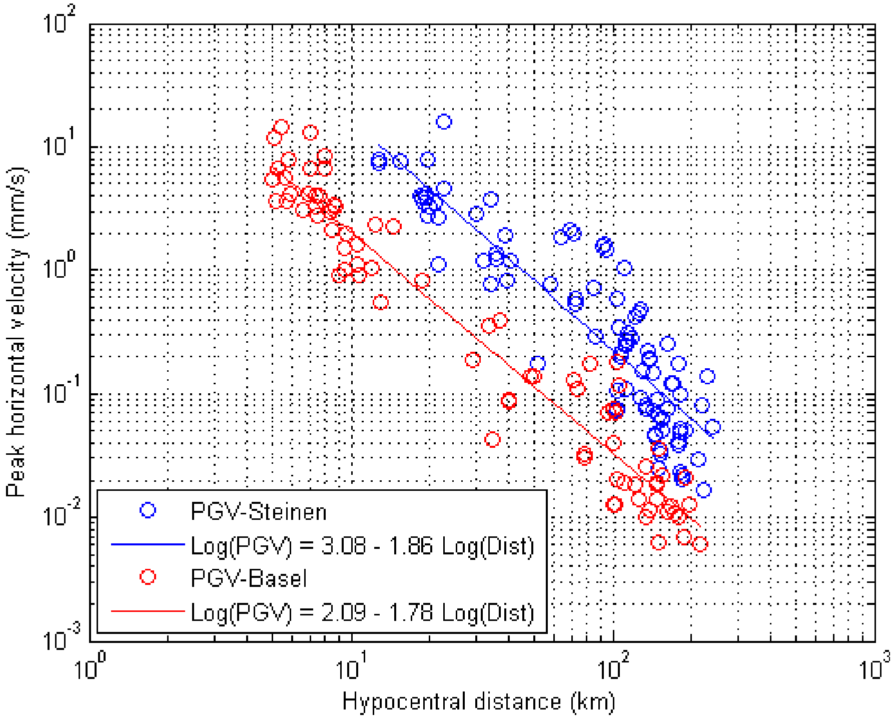
2006/12/08
03:06 ML 2.6
15:46 ML 2.7
16:48 ML 3.4
20:19 ML 2.5

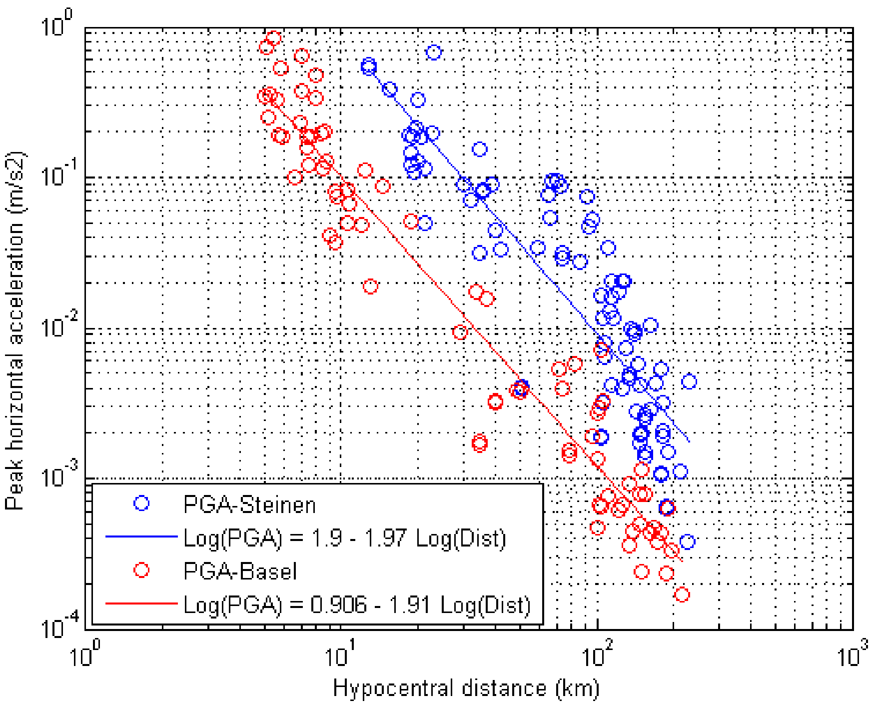
Häring et al., Geothermics (2008)



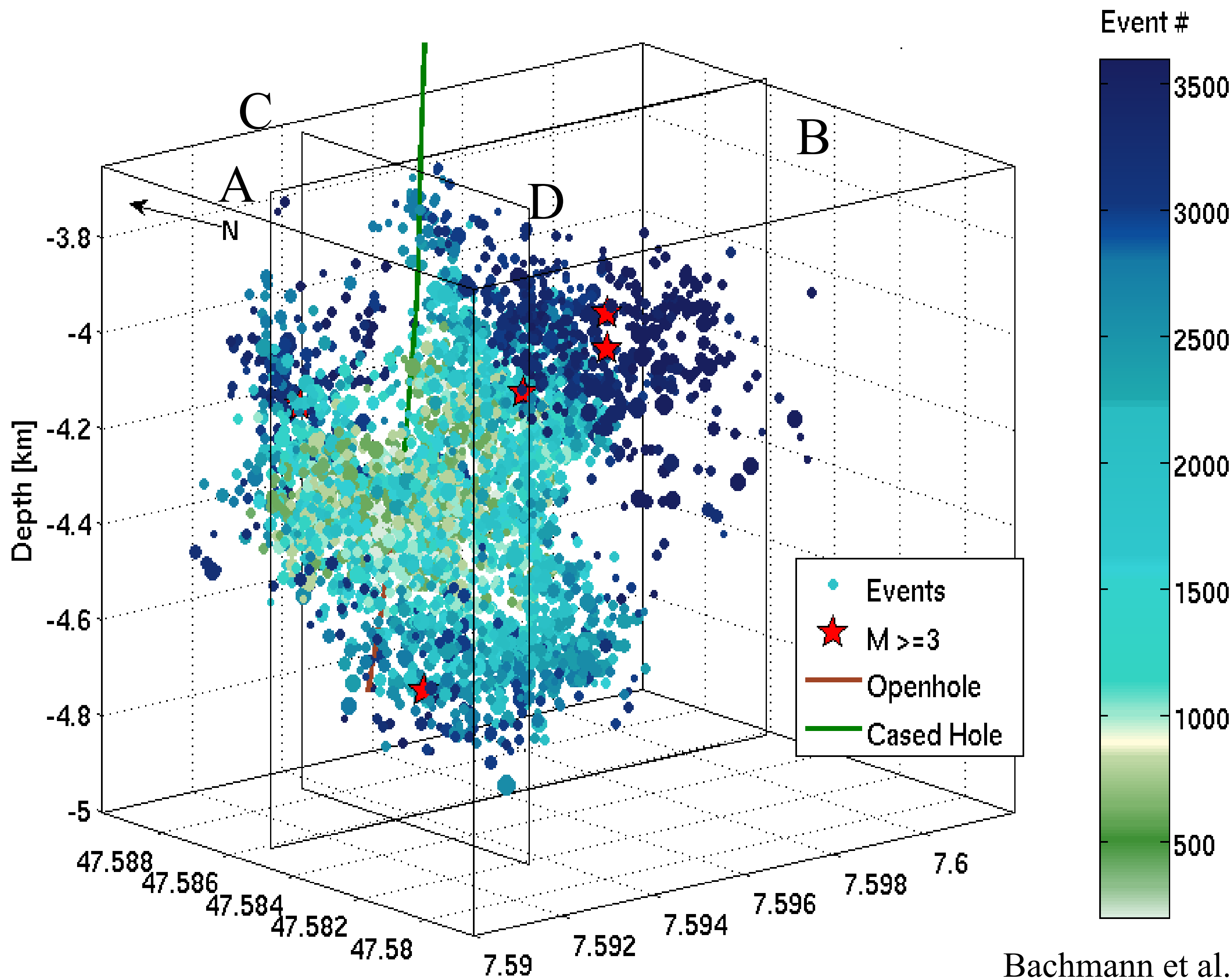
Geothermal Explorers, Ltd. (after Bommer et al. 2006)

Basel ML 3.4: PGV > 10 mm/s, PGA > 5% g



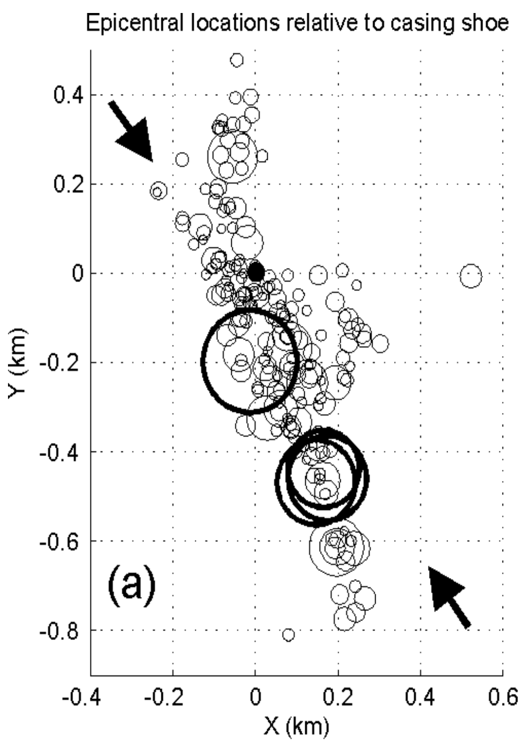


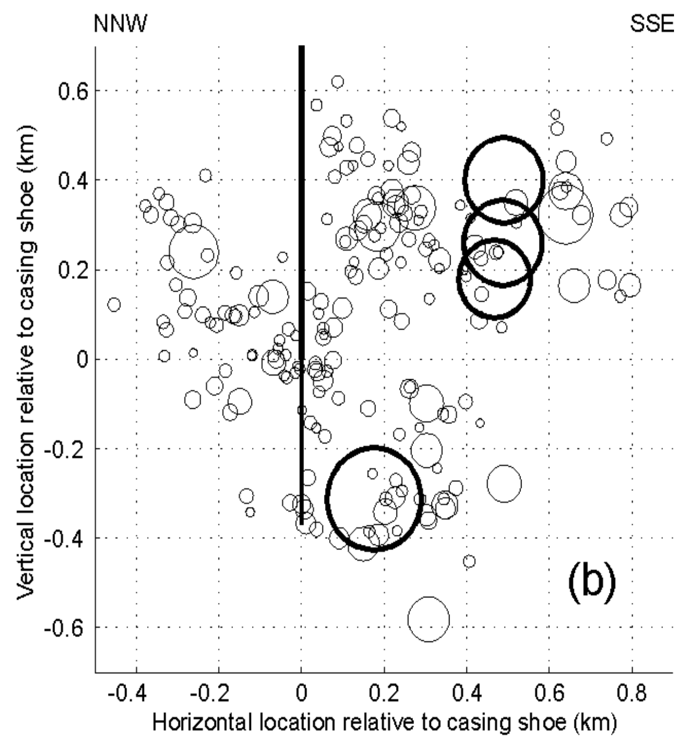
PGV and PGA of Basel (ML 3.4) and Steinen (ML 4.2) scale exactly as expected from their magnitude difference: There is nothing unusual about the induced Basel event



Bachmann et al. (2010)

Epicenters

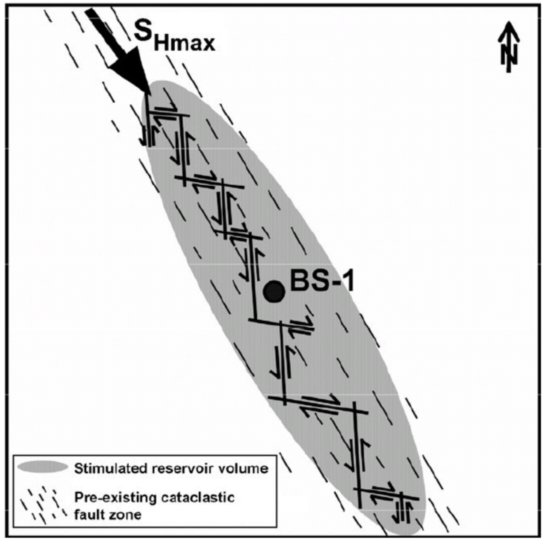




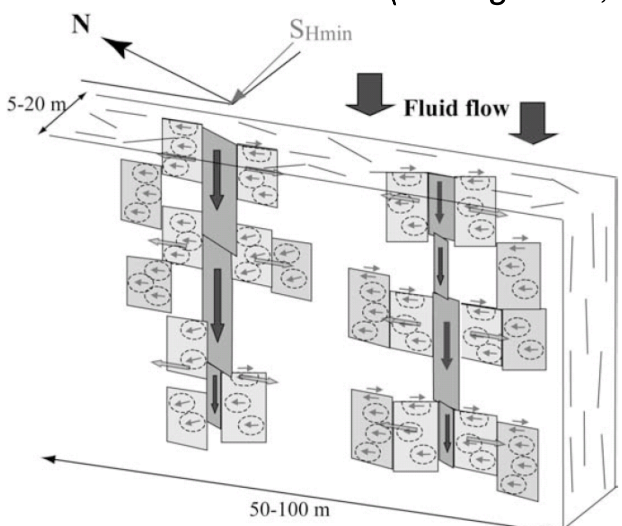
Focal depths

- The earthquake hypocenters form a steeply dipping NNW-SSE striking planar structure with a diameter of 1.2 km at a depth of 4-5 km. The overall orientation is close to the direction of the maximum horizontal stress.
- On a **local scale** the seismic events have contributed to both a release of stress and a transfer of stress. The latter is the cause of aftershocks.
- However on a **regional scale**, the overall stress release due to the seismicity induced by the Basel geothermal project is negligibly small and thus has not reduced the probability of occurrence of a possible larger earthquake.

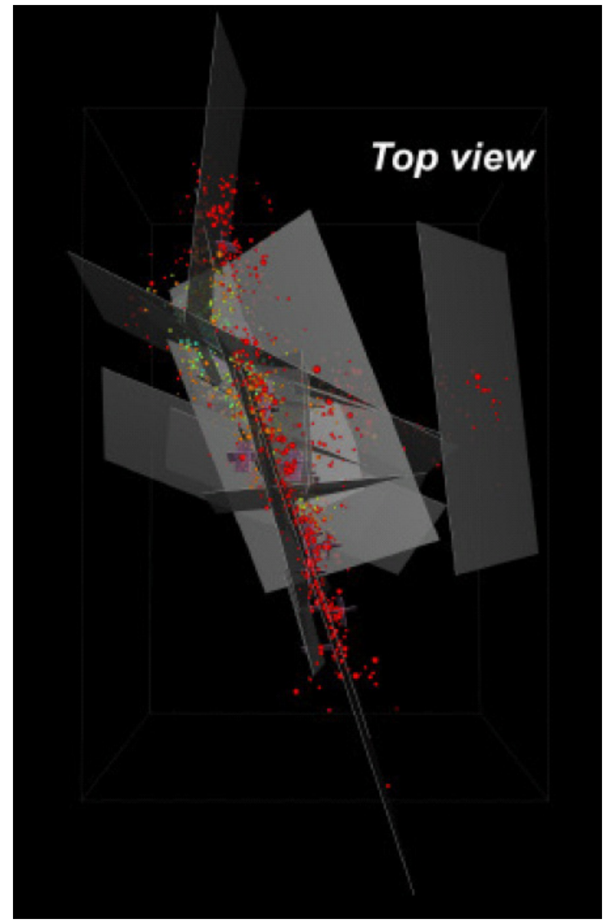
Reservoir models



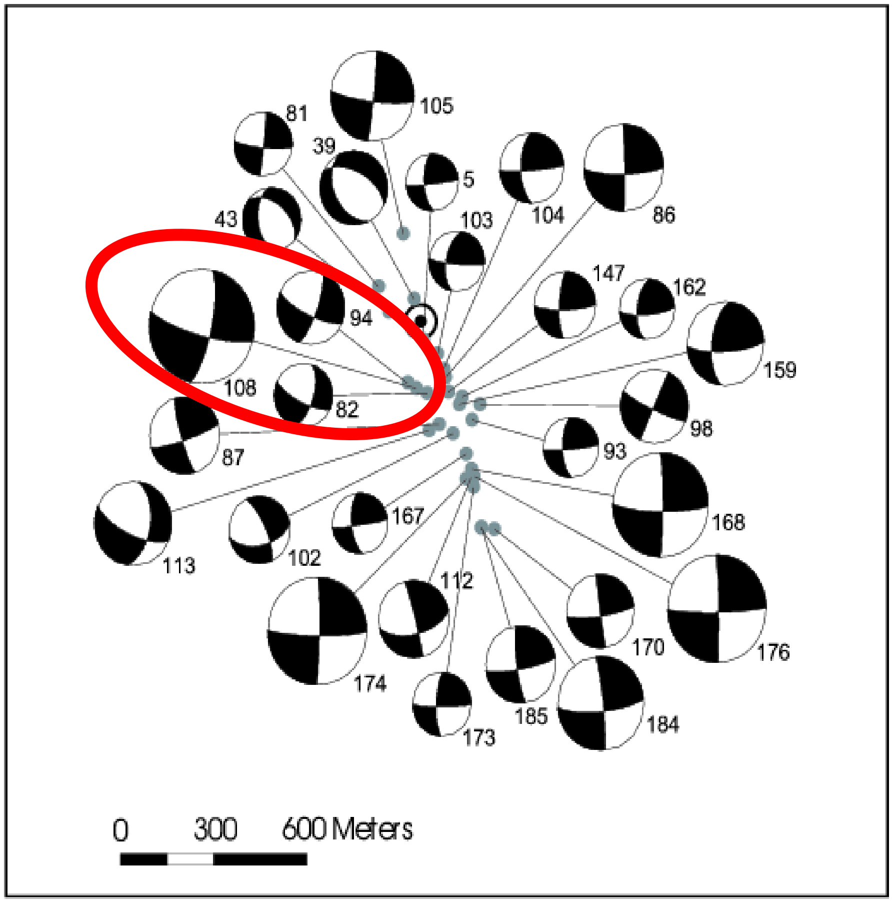
(Häring et al., 2008)

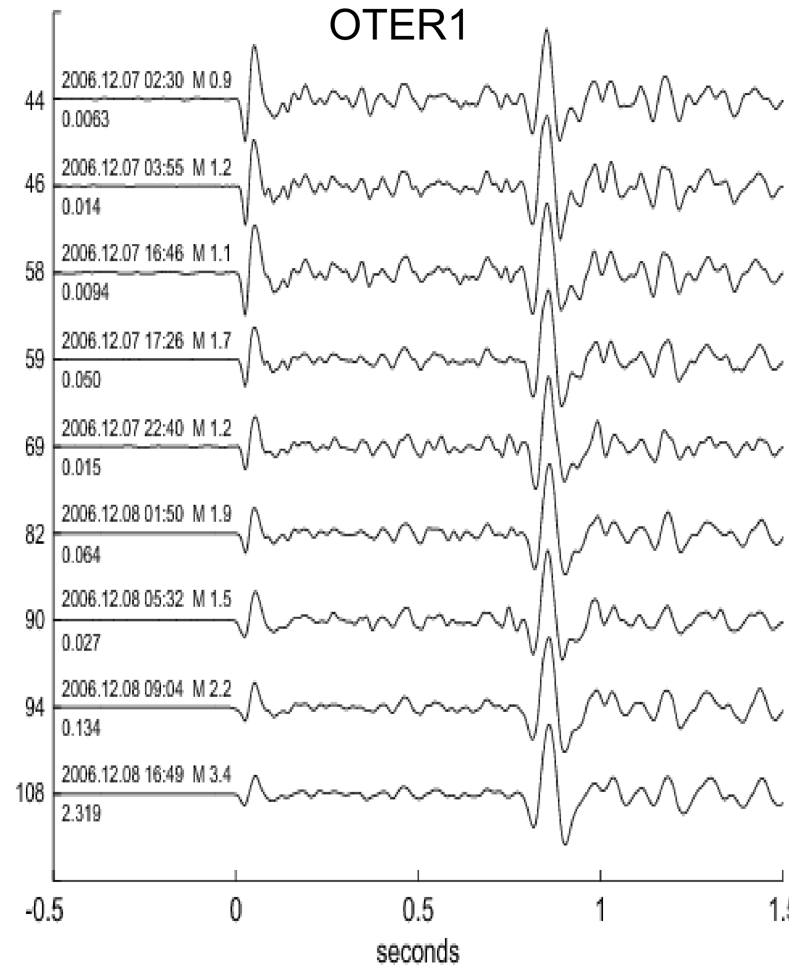


(Evans et al., 2005)



(Baisch et al., 2009)

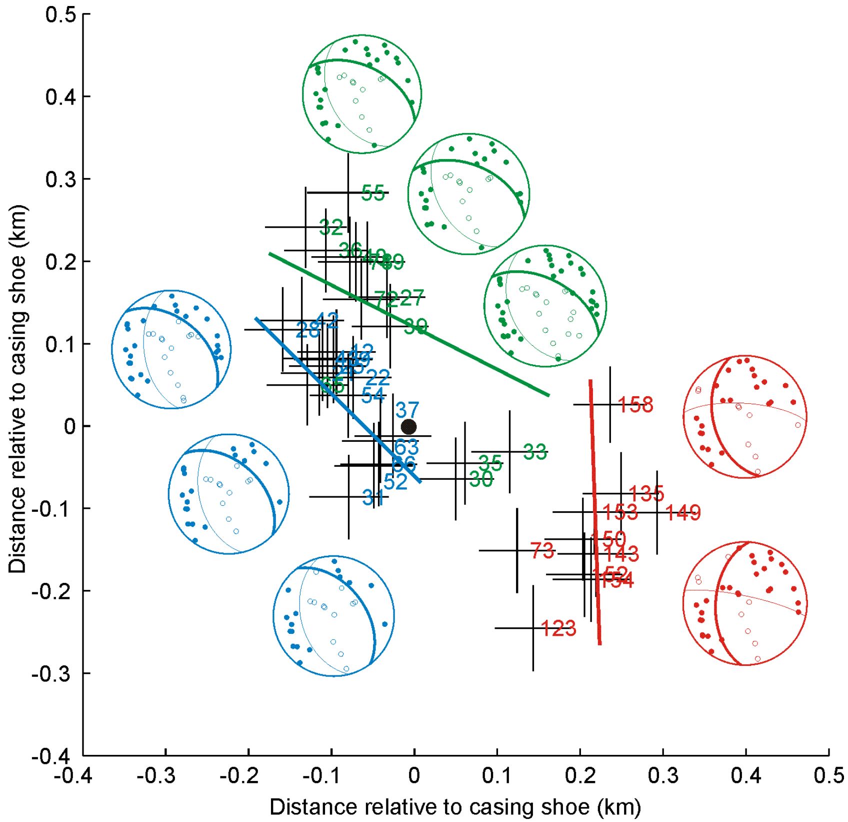




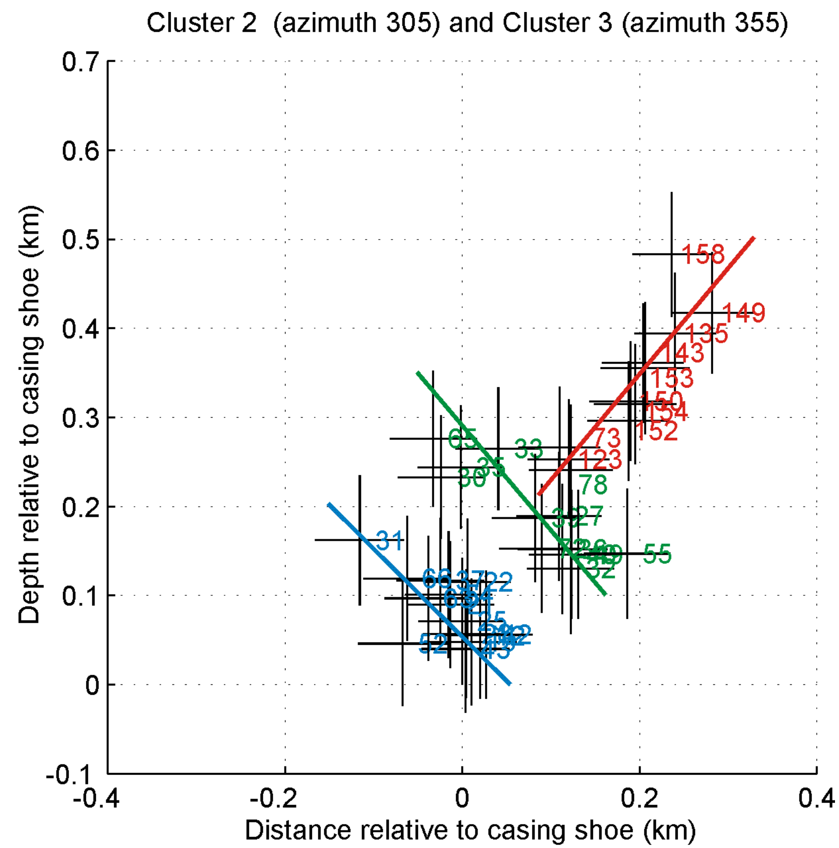
Deichmann & Giardini (SRL, 2009)

Three event clusters

Mapview



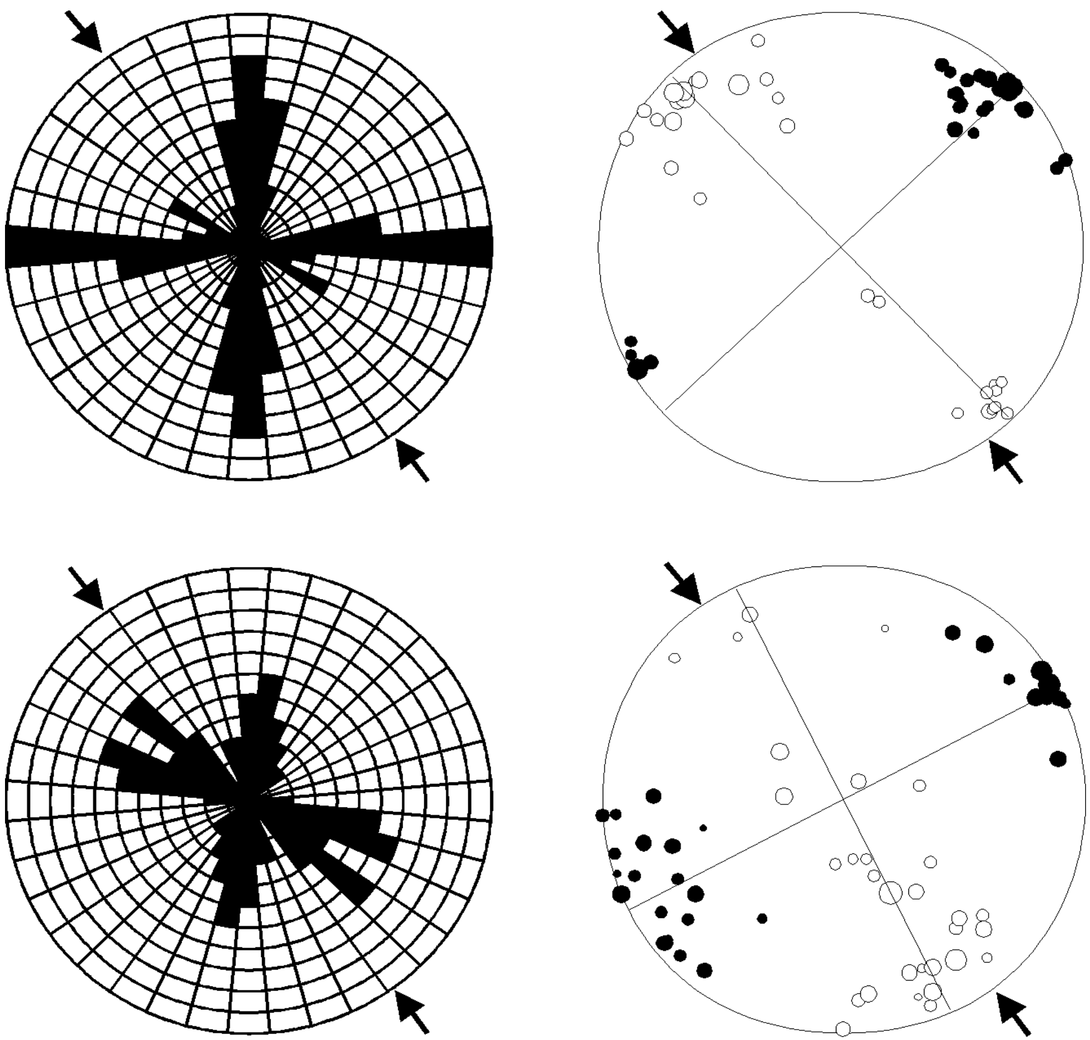
Depth cross-section



Fault segments or patches several 100 meters long.

Oriented obliquely to the overall strike of the seismicity.

Strike of nodalplanes | P- and T-axes



Basel city:

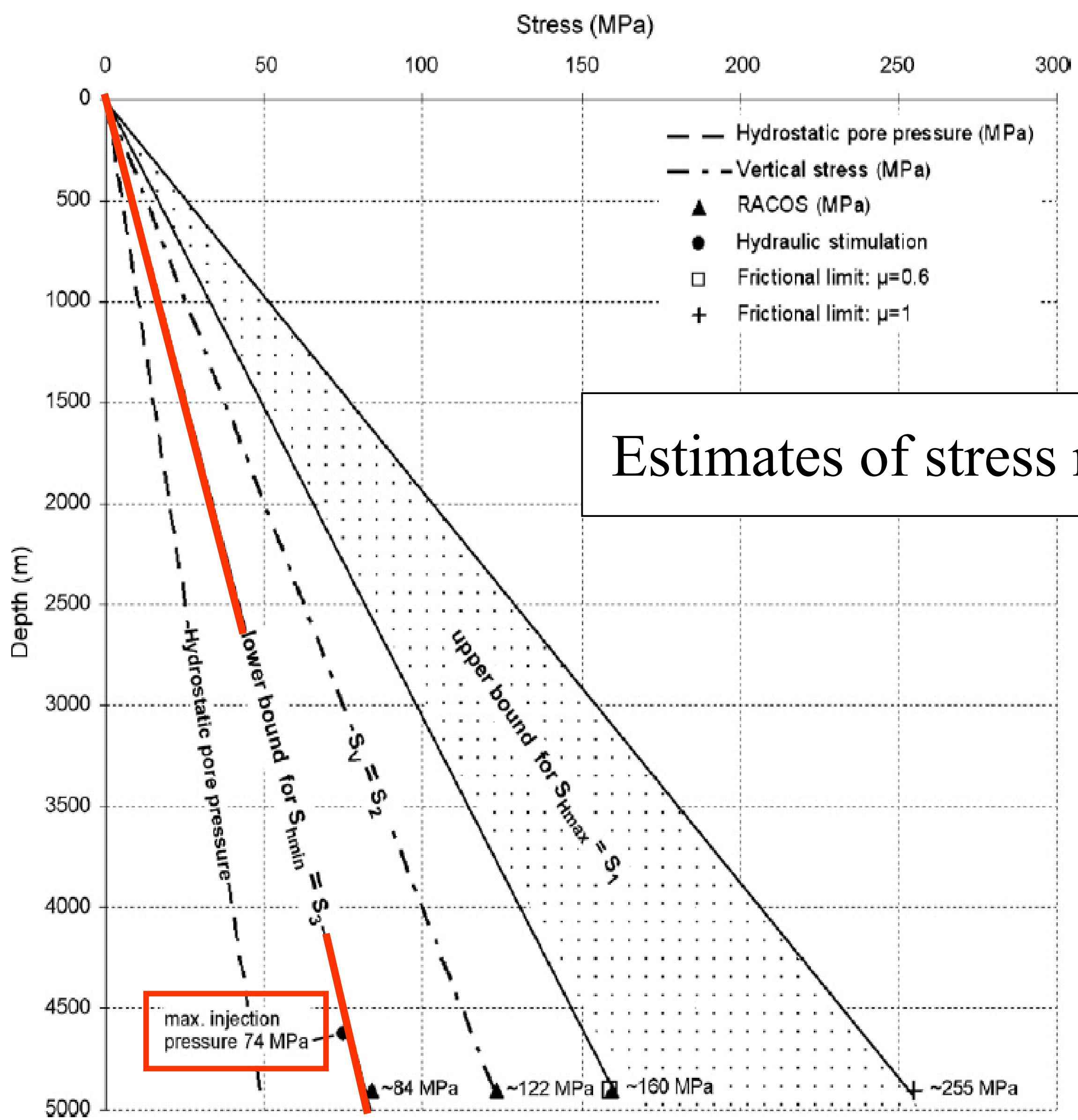
Induced earthquakes

Basel region:

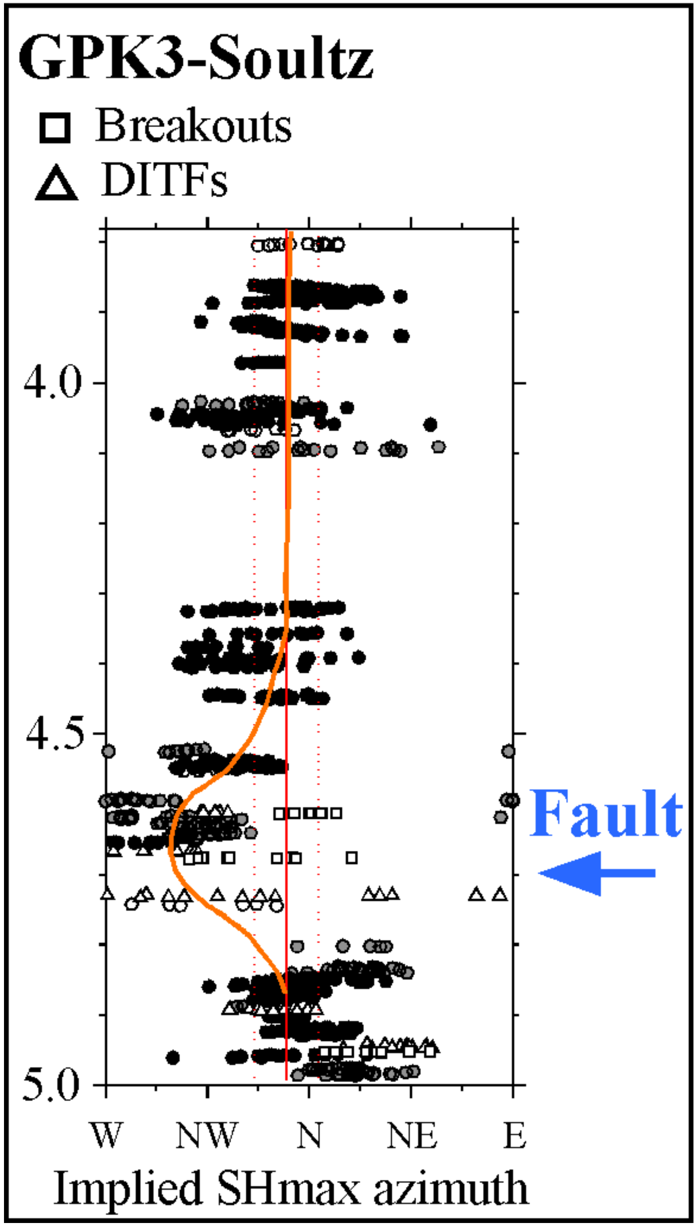
Natural earthquakes

Deichmann & Giardini (SRL, 2009)

Estimates of stress magnitudes



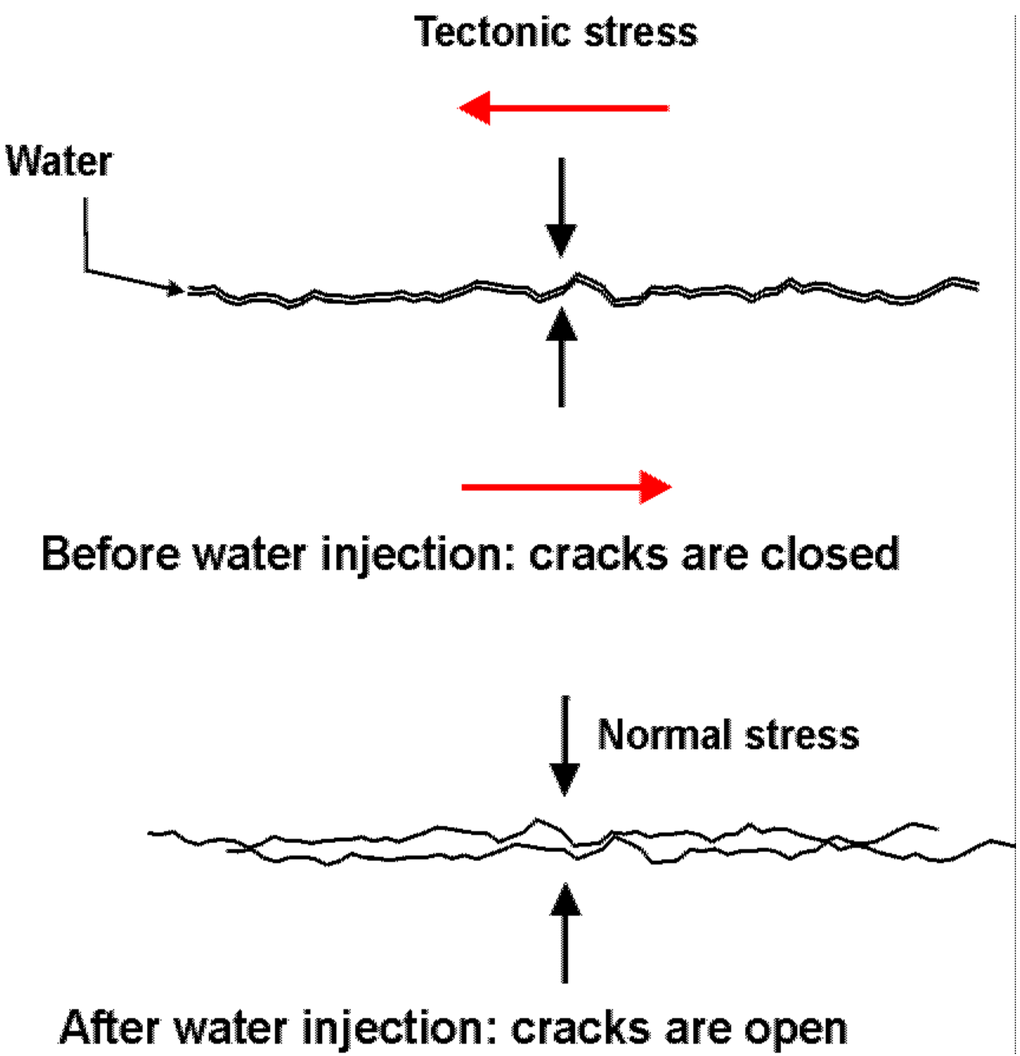
Häring et al., Geothermics (2008)



However stress can be quite heterogeneous, particularly surrounding a pre-existing fault.

And fault strength is likely quite variable as well.

Conceptual model of induced events



- The Injection of water into the underground and the consequent rupture processes are an essential ingredient of the exploitation of engineered geothermal systems.
- The driving force for the induced seismicity is the ambient tectonic stress.
- The water serves only to reduce the strength of pre-existing fractures.
- Thermal stresses and chemical alterations during the operational phase can also have a weakening effect.
- The physics of *induced* and *triggered* seismicity is identical.

The fundamental processes are understood, but in individual cases we do not have sufficient information to make quantitative estimates of hazard before the start of a project

Key question: why do some geothermal projects induce felt events and others do not?

- Tectonic stress?
- Rock friction?
- Depth?
- Injection pressure? volume? duration?

- How much permeability enhancement is seismic/aseismic?
- What is the role of larger magnitude events?
- Do we need larger magnitude events?

Largest event magnitudes at EGS sites

The largest events tend to occur during stimulation or shortly following stimulation injections when high pore pressures trigger in stress release.

Fenton Hill, **New Mexico** (2.8 km & 4.2 km): $M_m \sim 1.5$

Rosemanowes, Cornwall (2.2 km): $M_L = 1.9$ (Mildly felt)

Hijiori, Japan (1.8 & 2.2 km): $M_L = 2.4$ (Mildly felt)

Soultz, France (3.5 km): $M_L \sim 2.0$

Soultz, France (5 km): $M_L = 2.9$ (Felt)

Basel, Switzerland (5.0 km): $M_L = 3.4$ (Strongly felt – minor non-struct. damage)

Cooper Basin, Australia (4.1 km): $M_L = 3.7$ (Felt)

Note:

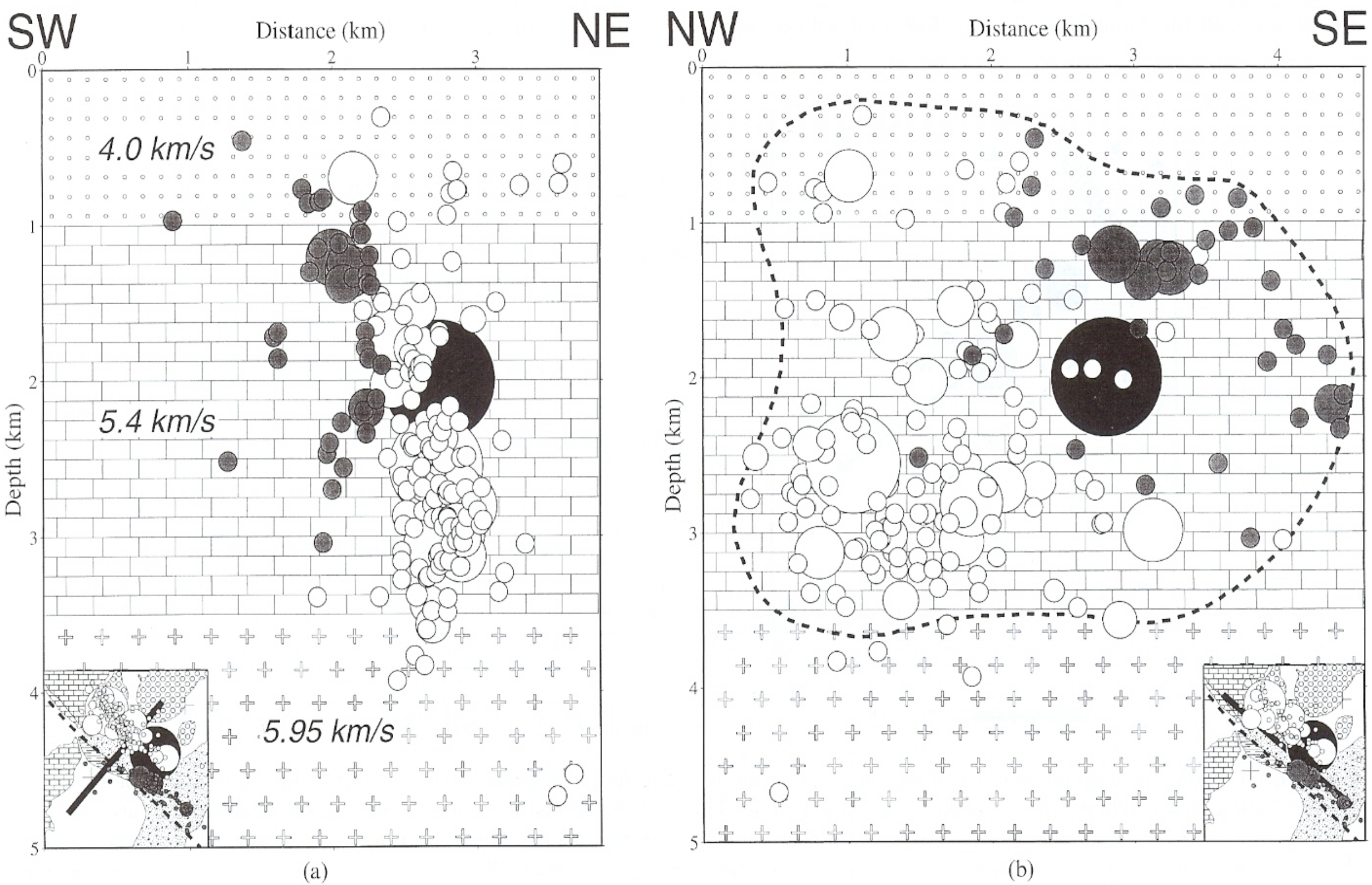
- The largest events induced by EGS activities to date are comparable to or smaller than the largest events recorded for other types of induced seismicity.
- Not all deep EGS sites produce felt events during large stimulation operations.

Why is the hazard due to induced earthquakes often underestimated?

Some misconceptions:

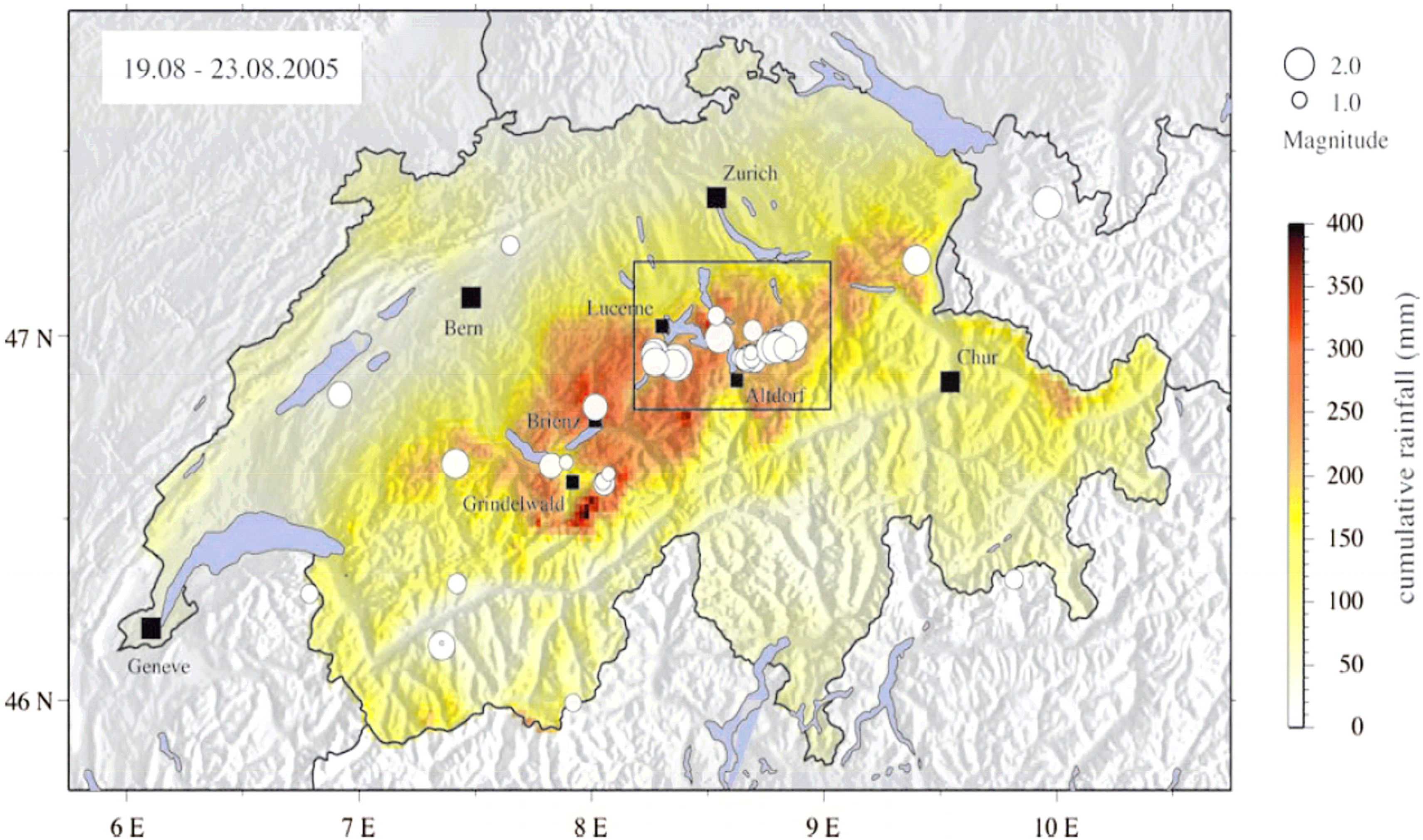
- Earthquakes occur only at greater depths
- Earthquakes occur only in the crystalline basement
- Earthquakes will only be induced by massive perturbations

The Magnitude 5.3 Earthquake of Annecy, 1996



Thouvenot et al., GJI (1998)

Rain-induced earthquakes, August 2008



Husen et al., GJI (2007)

Energy demand will increase, and thus also the pressure to exploit the earth's crust to extract heat by water injection and circulation, as well as to store large quantities of CO2.

EGS carries the potential for covering a significant part of our energy budget, if the associated seismic risk can be reduced to acceptable levels.

Industry and regulatory agencies are looking to seismology for guidance.

A Basel-type risk study is not possible a-priori for new projects.

We need a step-wise approach that allows to re-evaluate the risk and mitigation measures as new information becomes available in the course of project realization.

Deterministic modelling tools for the simulation of fluid-fault interaction are becoming more sophisticated. The results obtained with these tools will certainly add to our basic understanding of the processes underlying injection-induced seismicity.

However many of the basic parameters, such as the state of stress and the location, orientation and strength of faults are known poorly or not at all prior to drilling and stimulation.

The El Salvador- or Basel-type traffic-light system to guide mitigating measures during stimulation needs to be refined.

New statistical methods combined with physical models could provide information in terms of probabilities for the occurrence of felt or damaging earthquakes a useful time period in advance.

This requires more sophisticated real-time monitoring of the ongoing induced seismicity, which includes faster and more accurate locations and magnitudes as well as other source parameters, such as source dimensions, stress drops and b-values.

Conclusions

Although some deep geothermal and CO2 storage projects have been implemented with success, the technolgies are still far from routine operations.

→ each new project is still a pilot-project!

Therefore permitting of new projects should require

- A full risk study (including the risks of induced seismicity)
- Comprehensive borehole measurements (in particular stress)
- Comprehensive monitoring of all operational parameters
- Detailed monitoring of potential seismicity
- Post-stimulation borehole measurements
- Open and professional communication strategy (not just PR), as well as open access to data.