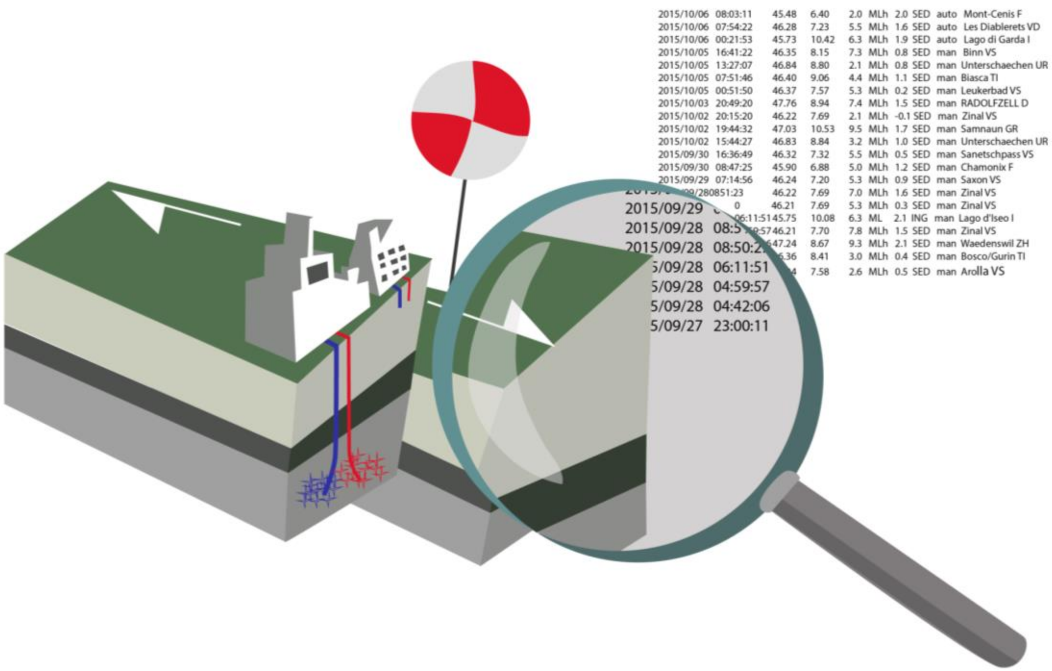
Challenges for limiting induced seismicity

Stefan Wiemer - with contributions by many others

Sion, 13.9.2016



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SUPPLY of ELECTRICITY

DESTRESS

Demonstration of soft stimulation treatments of geothermal reservoirs

70 NFP

Energiewende
Nationales Forschungsprogramm

In cooperation with the CTI

Energy funding programme
Swiss Competence Centers for Energy Research

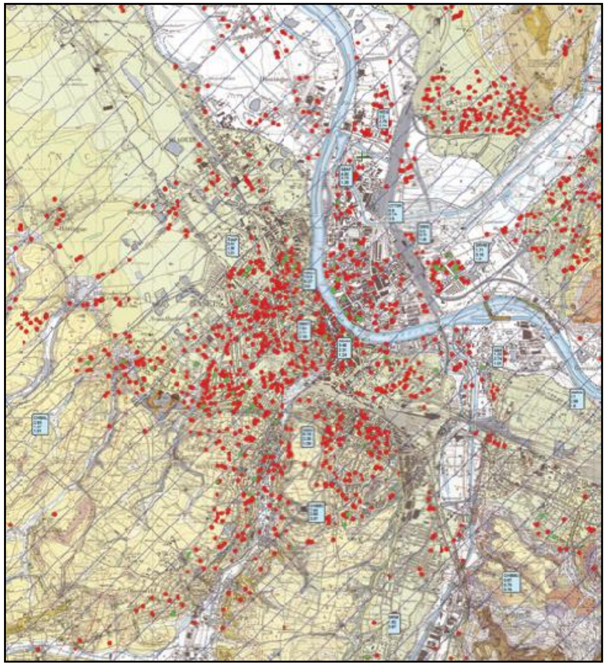
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

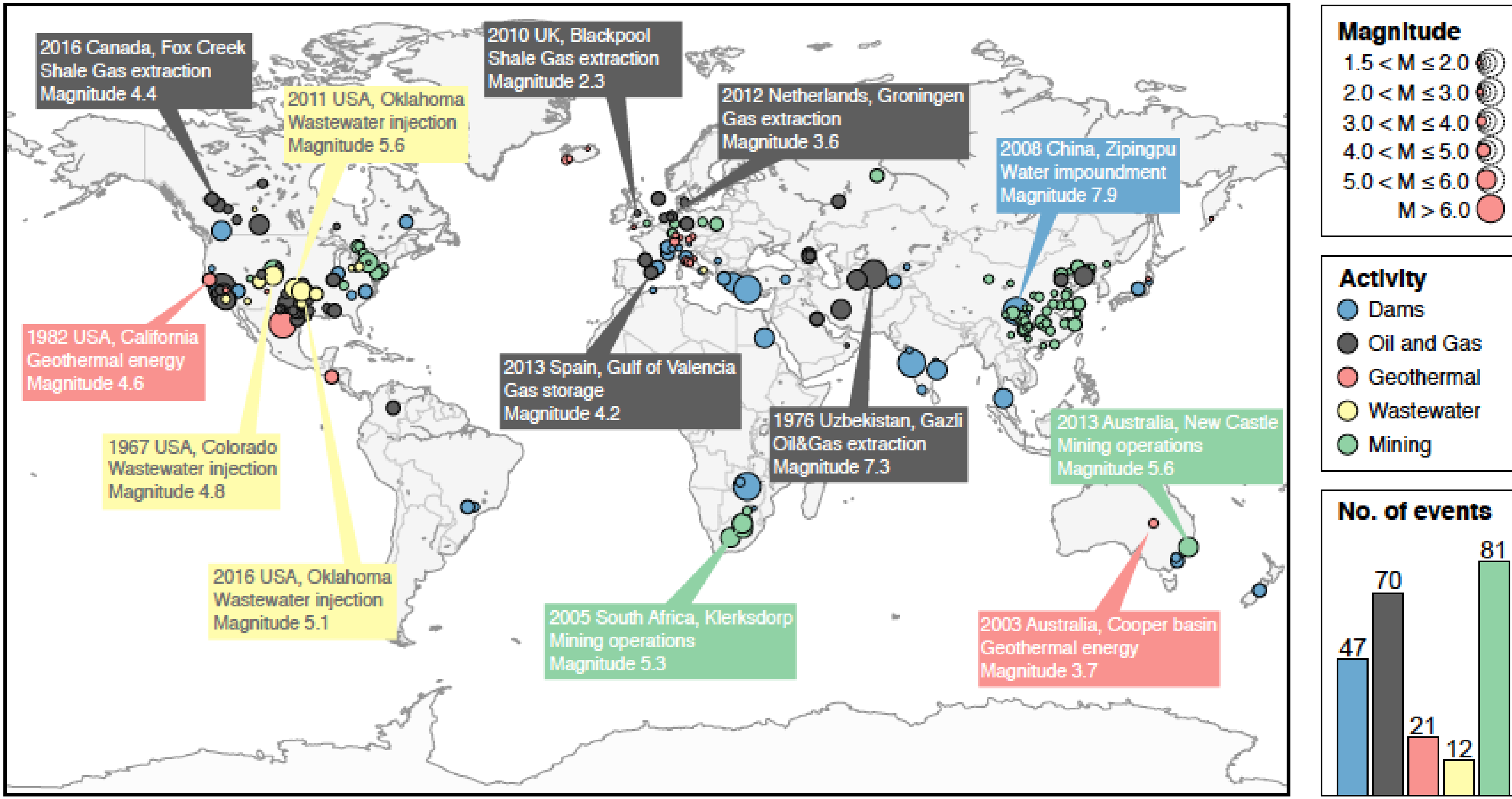
Commission for Technology and Innovation CTI

At least since Basel 2006 - we all known Induced Seismicty is a problem

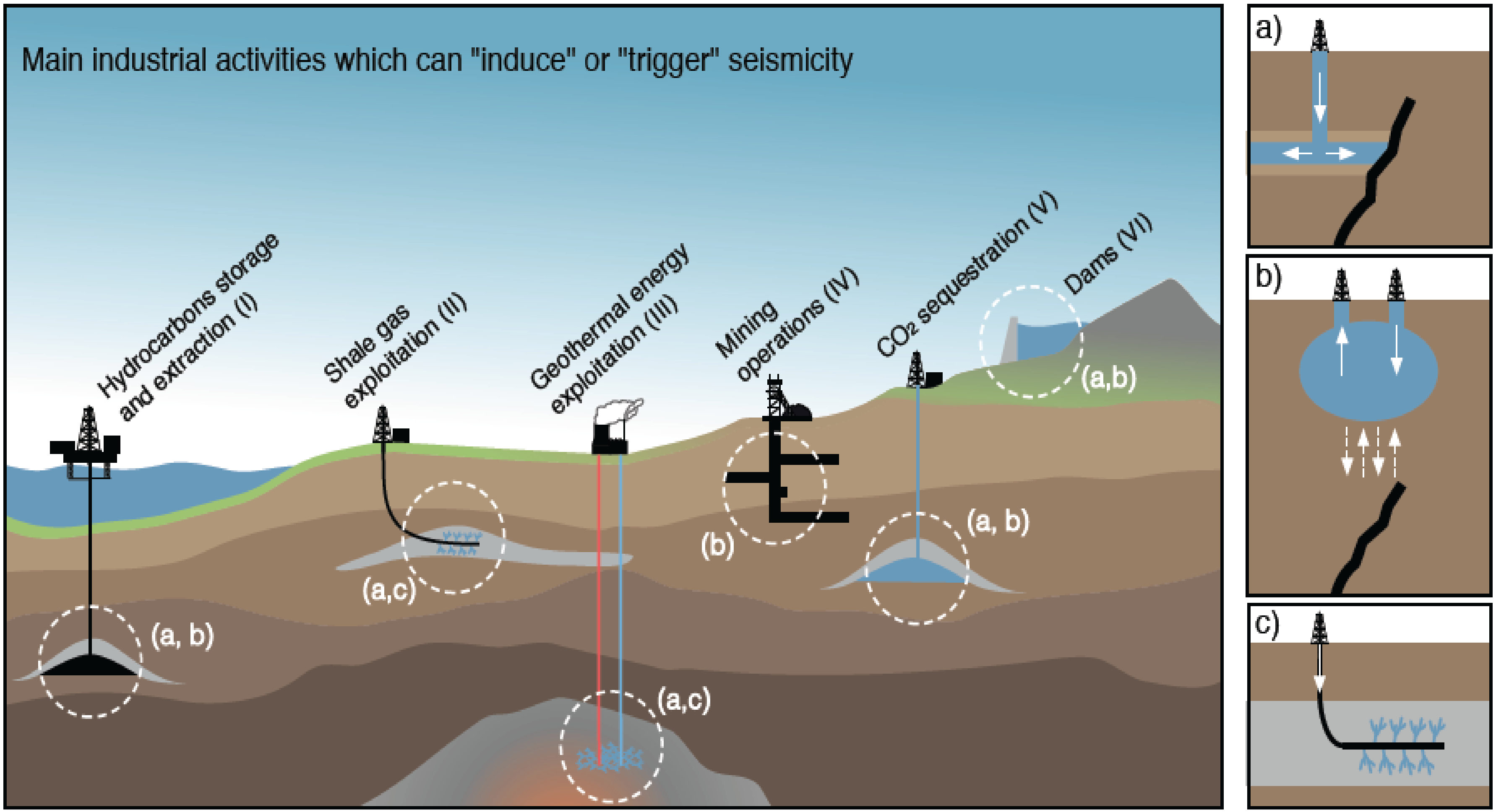
But it is 2016 – have we made progress
- are we the there yet?



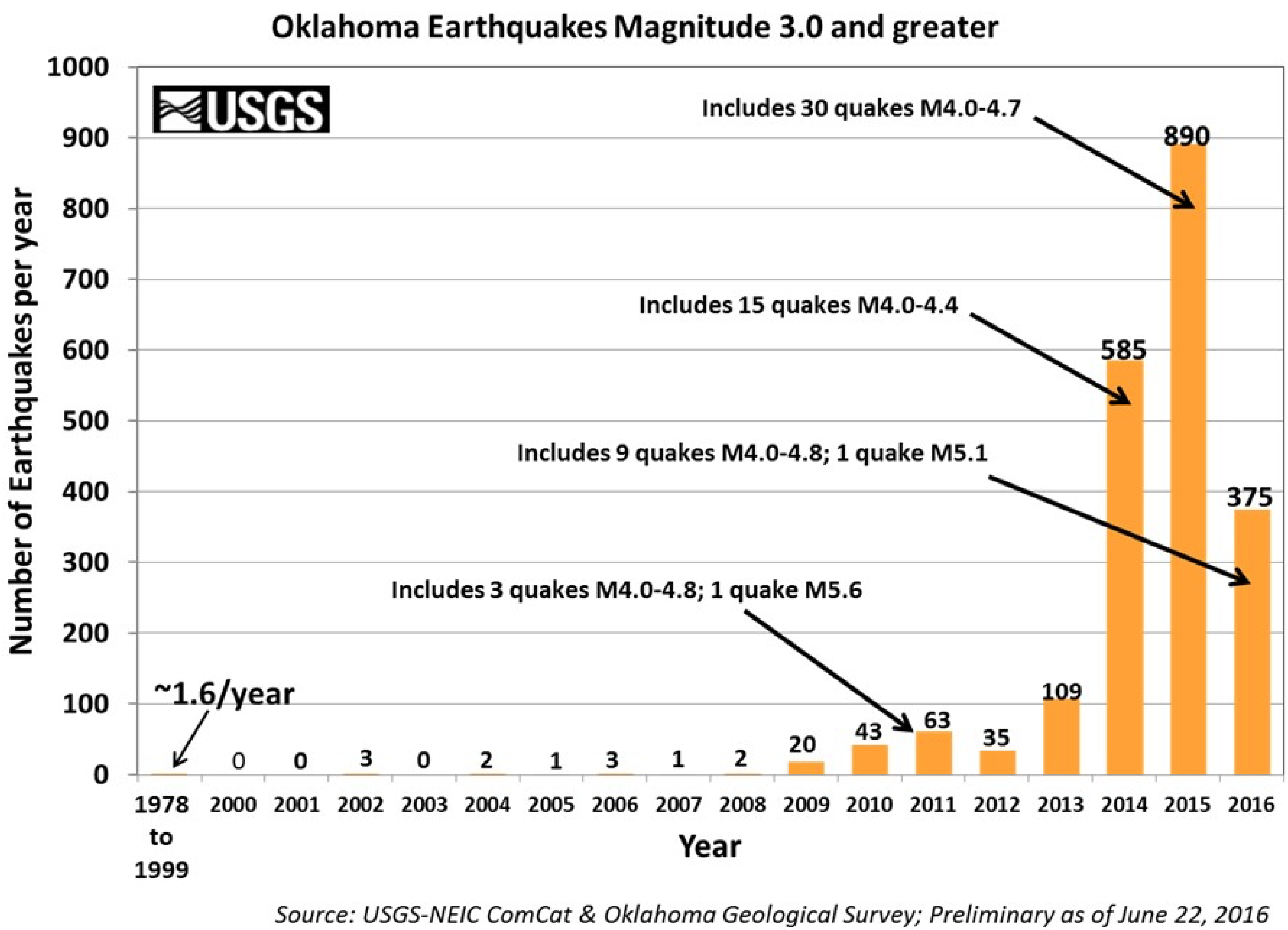
Induced Seismicty: A global challenge...



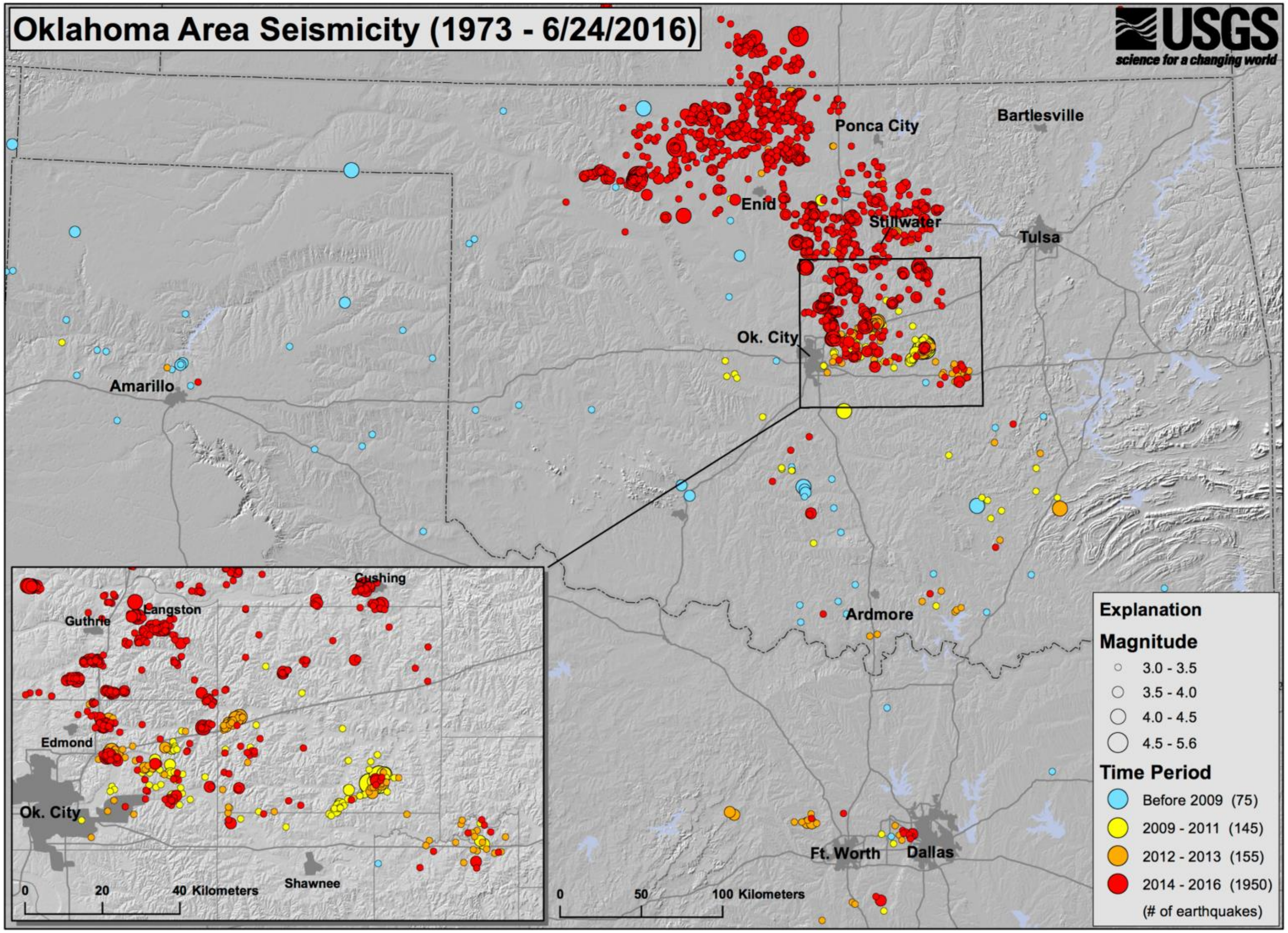
... with many causes ...



Are we there yet ? Not in the USA …



Are we there yet ? Not in the USA …



Are we there yet ? Not in the USA …

U.S.

Oklahoma Orders Shutdown of Wells After Record-Tying Earthquake

By NIRAJ CHOKSHI and HENRY FOUNTAIN SEPT. 3, 2016

Stonework fell to the sidewalk at the corner of Sixth and Harrison Streets in Pawnee, Okla., after a 5.6-magnitude earthquake struck the area on Saturday morning. Lenzy Krehbiel-Burton/Reuters

Oklahoma officials on Saturday ordered oil and gas operators to shut down three dozen wastewater disposal wells following a 5.6-magnitude earthquake that tied a record as the strongest in state history.

The quake, centered near Pawnee, rattled the state just after 8 a.m. Eastern

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The lawyers have arrived!

Are we there yet ? Not in the NL…

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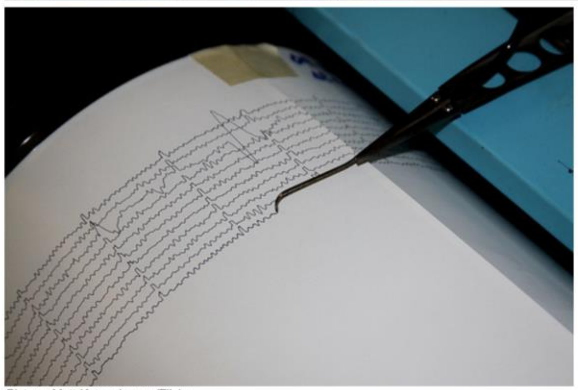
NETHERLANDS

EARTHQUAKES DAMAGED AT LEAST 100,000 GRONINGEN HOMES

Posted on Sep 5, 2016   by Janene Pieters



Picture: Matt Katzenberger/Flickr

At least 100 thousand Groningen residents live in a home damaged by earthquakes caused by extraction in the province. A quarter of them reported damage more than once, according to a s the University of Groningen, public health service GGD and the municipality of Groningen, NOS

The researchers looked at NAM's data on damage reports as well as figures from Statistics Net and the Land Registry. Since 2012 about 70 thousand earthquake damage claims were filed. S thousand of these were handled and paid. The other 15 thousand are still in various stages of p

According to the researchers, the actual figures may be much higher as the damage in some h yet to be discovered. They also point out that many damaged homes lie outside the so-called "earthquake zone" and are therefore not included in the figures.

A previous study showed that earthquake damage to home can lead to health problems for thos affected, ranging from insomnia to heart problems. About 40 percent of Groningen residents do safe in their homes, compared to 15 percent in all of the Netherlands. Among Groningen reside whose hoes were it by an earthquake more than once, only a third still feel safe in their homes.

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101 schools in Groningen need action because of earthquake risk

Education   June 7, 2016

Photo: Graham Dockery

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Shell and ExxonMobil regret Groningen earthquake problems

Business September 8, 2016

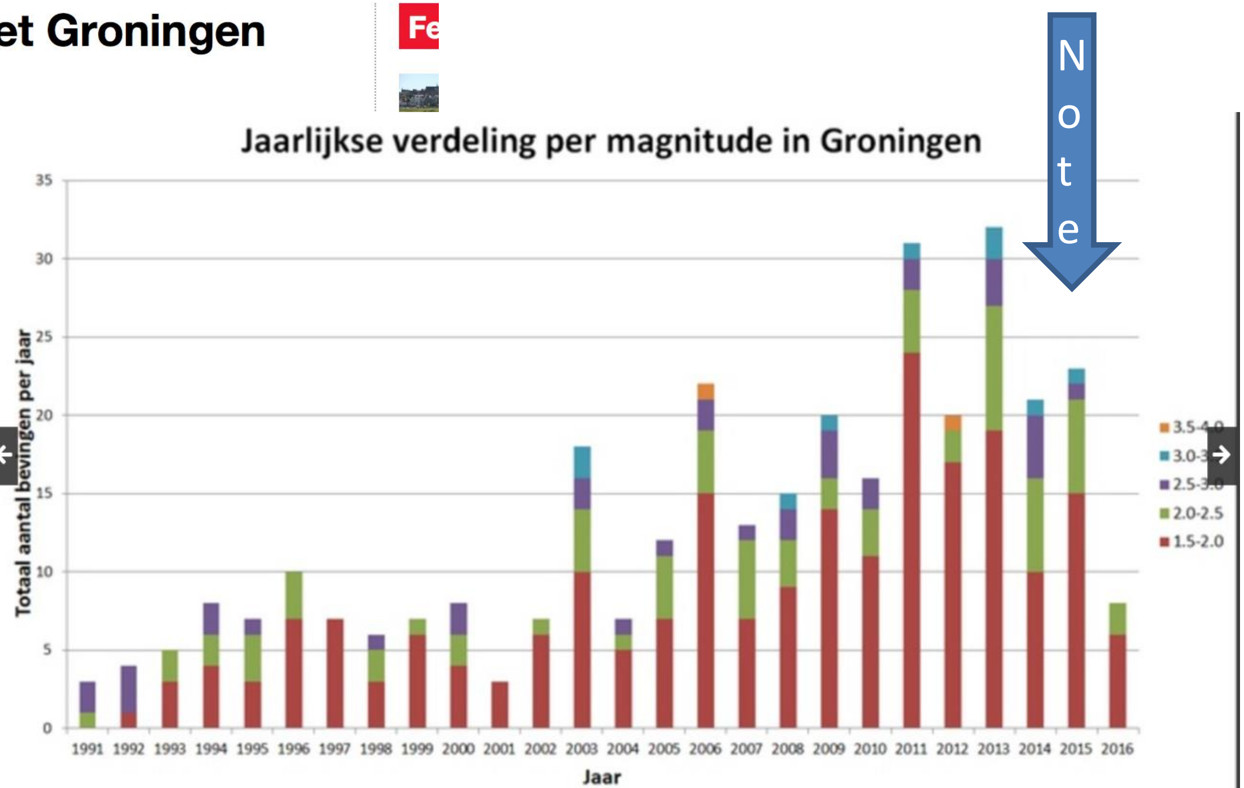
A condemned and shored-up cafe. Photo: Graham Dockery

The two i responsib Groninge regret for caused ir

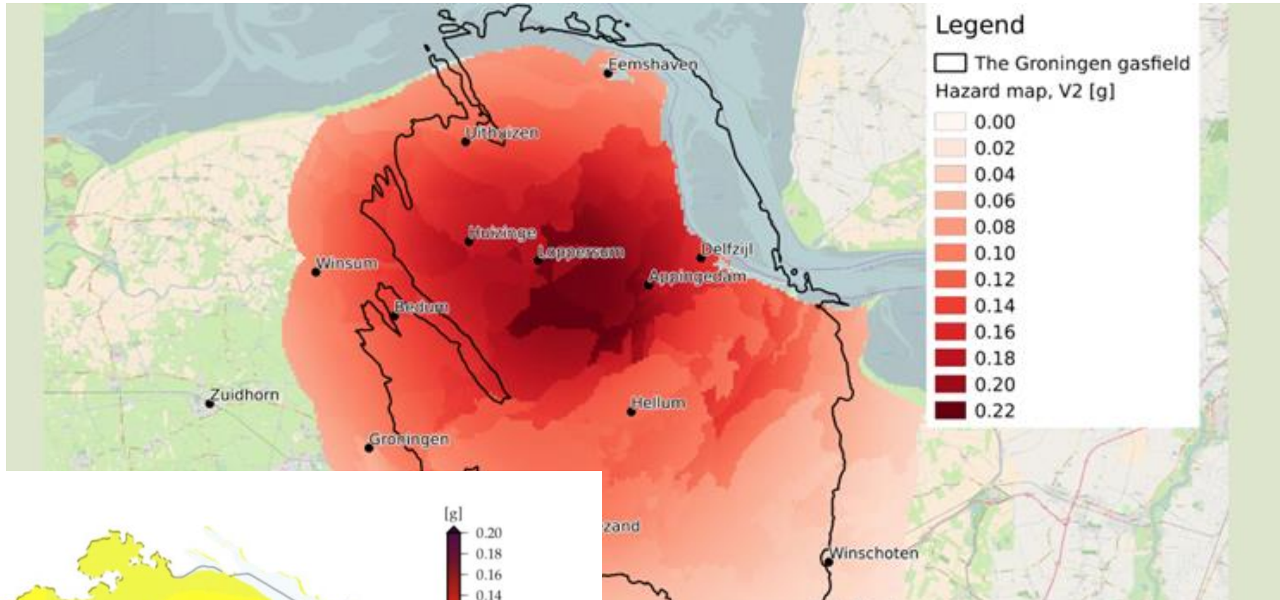
Officials r parliamer ExxonMo challenged by GroenLinks MP Liesbeth van Tongeren

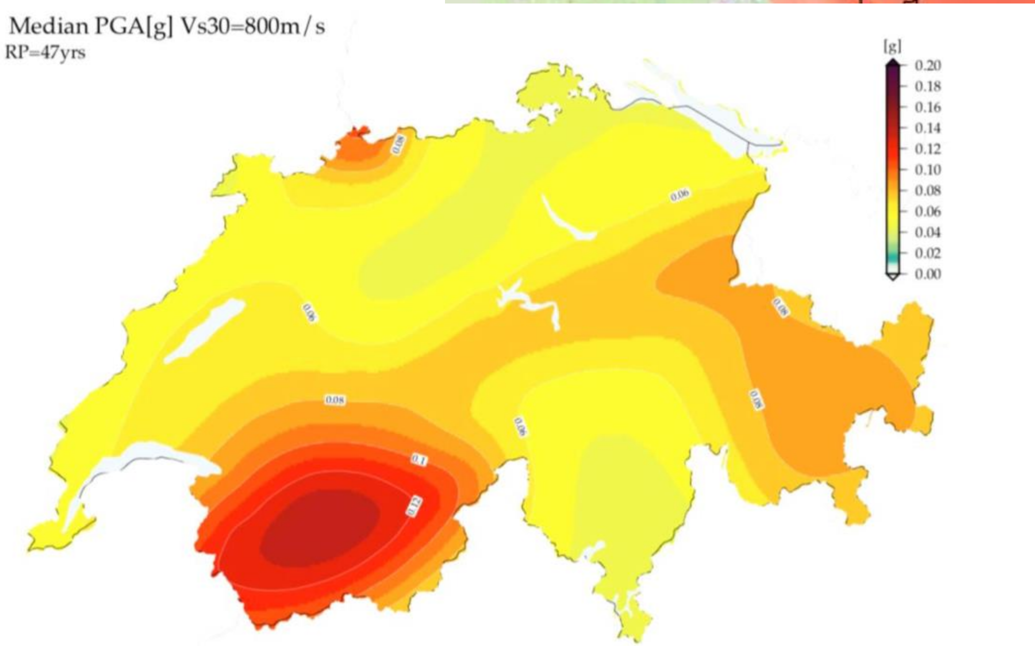
'We acknowledge that the people of Groningen are d caused by gas extraction, which we in the Netherlanc Shell Nederland president Marjan van Loon said.

'That is why the people of Groningen deserve our sup its regrets and I can fully support that. So I can say to

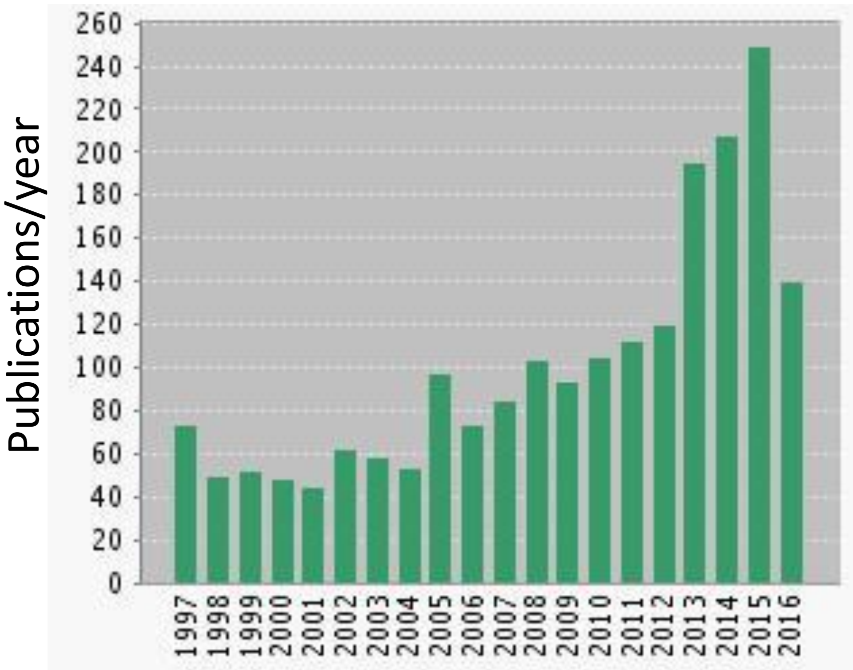


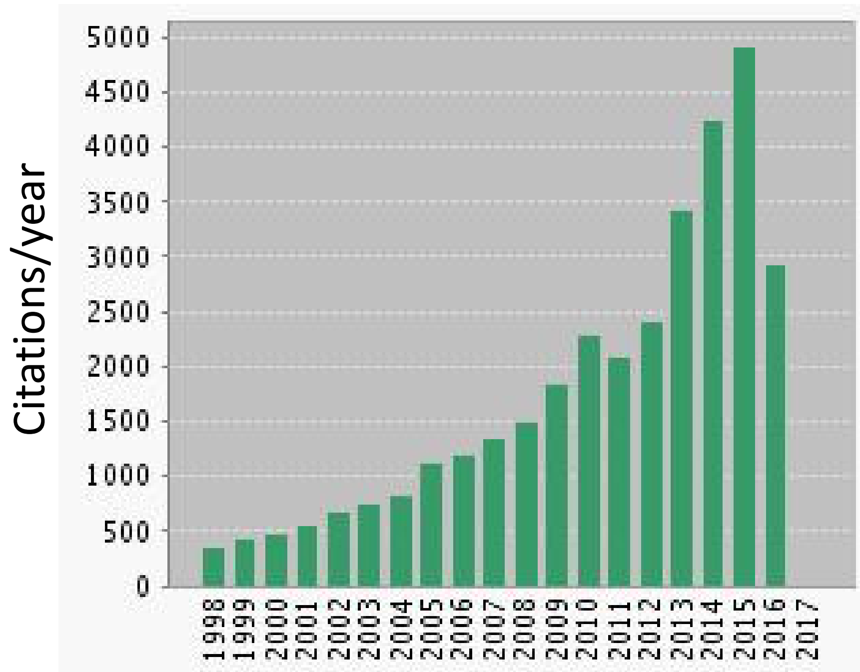
Beyond nuisance ...





Are we there yet ? The academic world is just getting started … (citiation '*induced seismicity*')





source: web of science, status Sept 2016

Some perspective

- Natural earthquakes matter more!
- Other topics may matter more (‘climate change’: 23’932 papers in 2015 alone…) .
- We are not powerless.

Are we there yet ? Status in Switzerland

4 Blick — Freitag, 9. September 2016

Erdbeben-Simulation im Felslabor

Dieser Forscher schlägt Wellen

Der Eingang: Das Felslabor befindet sich in 450 Metern Tiefe.

Im Felslabor Grimsel: Florian Amann (41) mit einer Sonde für die Untersuchung der Bohrlöcher. An der Spitze ist eine Kamera.

Attila Albert (Text) und Stefano Schröter (Fotograf)

In 450 Metern Tiefe am Grimselpass im Berner Oberland fühlen Wissenschaftler dem Berg den Puls. In einem Felslabor arbeiten sie an der Energie der Zukunft – und daran, **deren grösstes Risiko deutlich zu verringern: unerwünschte künstliche Erdbeben.**

Ein 3,30 Meter hoher Tunnel führt zum unterirdischen Labor. Der Boden ist feucht, denn **der Räterichsbodensee über uns presst das Wasser durch den Granit.**

15 Bohrungen hat das Team um Florian Amann (41) von der ETH Zürich in den Fels getrieben, bis zu 48 Meter tief. In ihnen stecken **Kameras, Glasfaserkabel und Sensoren,** welche Verschiebungen und Druckveränderungen registrieren.

«Wir forschen daran, die Geothermie effektiver zu machen und das Risiko von Beben in einem akzeptablen Rahmen zu halten», sagt er. Geothermie ist Energie aus heissem Tiefenwasser, diese soll in der Schweiz einen Teil des Atomstroms ersetzen. Um alle unsere Atomenergie abzulösen, bräuchte es 25 geothermische Kraftwerke.

110 Experten arbeiten für das Schweizer Kompetenzzentrum für Strombereitstellung. Sie prüfen, welche Wege sich das eingepresste Wasser im Fels sucht, der **in vier bis fünf Kilometern Tiefe bis zu 200 Grad heiss** ist, und welche Erschütterungen und Verschiebungen das heisse Wasser bis zur Rückkehr nach oben auslöst.

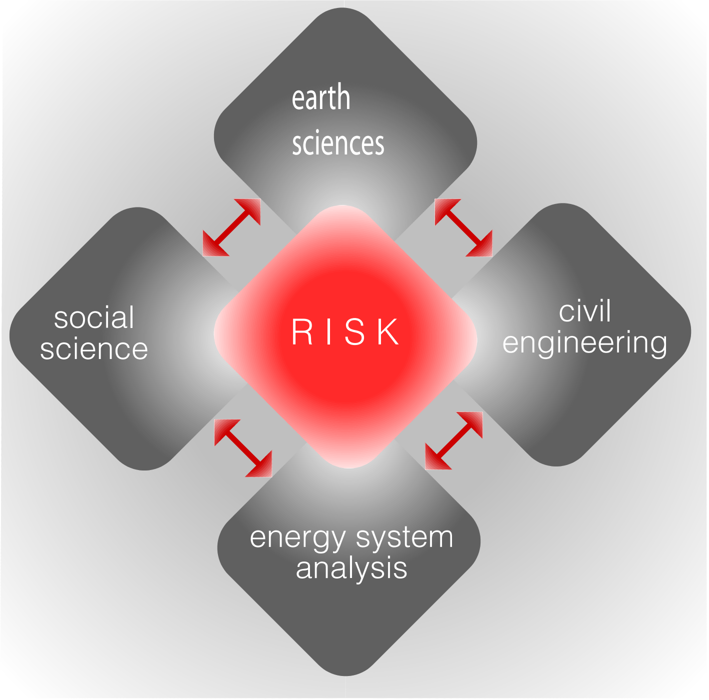
Ein Warnzeichen war eine Probebohrung 2006 in Basel: Das eingepumpte Wasser, das sich in der Tiefe erhitzen sollte, **löste 11 200 kleine Erdbeben aus. Mehrere davon mit einer Stärke von über 3,0 auf der Richterskala** verursachten kleinere Schäden. St. Gallen begrub 2014 ein Geothermieprojekt, weil das gefundene Wasservorkommen zu gering war. Aber auch im Sittertobel war es ein Jahr zuvor bei einer Spülung zu einem Beben gekommen.

Im Felslabor Grimsel soll das Unvermeidbare beherrschbar werden. Experte Ueli Wieland (58): **«Das Ziel sind Beben einer Stärke von maximal 2,5. Sie sind an der Oberfläche kaum zu spüren.»**

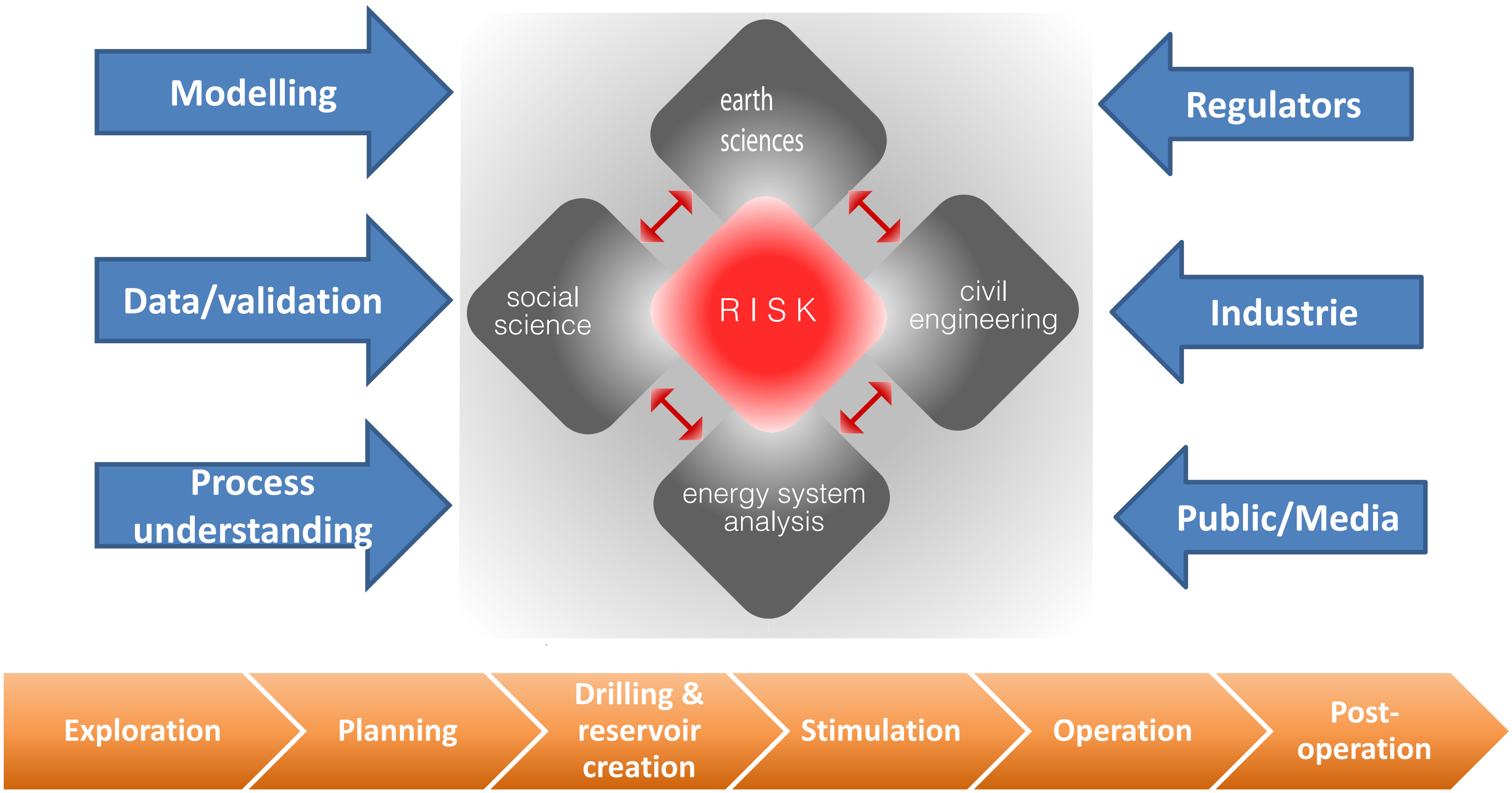
Interessierte können das Felslabor Grimsel besichtigen, die Touren sind kostenlos. Informationen: Telefon 056 437 12 82.

So why are we not there yet?

- Because induced earthquake risk governance is a very complex scientific/ engineering/societal/ economical (etc.) problem.
- No quick fixes, no silver bullet, no single measure that will simply solve the problem. Instead: A brick by brick, long-term approach that gradually improves the sustainability and the resilience of projects.
- A transdisciplinary and holistic approach is needed, integrating various disciplines as well as spatial and temporal dimensions.
- This is what the SCCER-SoE is doing!



Induced seismicity risk governance is a process – and it requires interfaces!



Check our our posters!

List of posters:

1) "Accident Risk Assessment for Deep Geothermal Energy Systems in Switzerland: An Update" by Matteo Spada, Emilie Sutra and Peter Burgherr

2) "A Bayesian Hierarchical Model for Hydropower Dam Accident Risk" by Anna Kalinina, Matteo Spada and Peter Burgherr

3) "Physical-Based Model of a Dam Failure Event" by Anna Kalinina, Matteo Spada and Peter Burgherr

4) "ENSAD v2.0 Hydro: a new interactive, GIS-based database for historical hydropower accidents worldwide" by Peter Burgherr, Matteo Spada, Anna Kalinina and Kim Wansub

5) "RIsk GOveRnance of electricity pOrtfolioS (RIGOROuS): Cross-technology and spatial tradeoffs of multiple risks" by Trutnevyte E., Berntsen P., Knoblauch T., Volken S.

6) "Long-term decay and possible reactivation of induced seismicity at the Basel EGS site", by Herrmann M. (other authors?)

7) "Controlling induced seismicity in EGS projects by a model-driven traffic light system", by A. Mignan, M. Broccardo and S. Wiemer

8) "Multi-risk in the Swiss landscape: The case of earthquake-triggered landslides", by A. Jafarimanesh, A. Mignan and D. Giardini

9) "Social discourses on deep geothermal energy" by Olivier Ejderyan and Michael Stauffacher

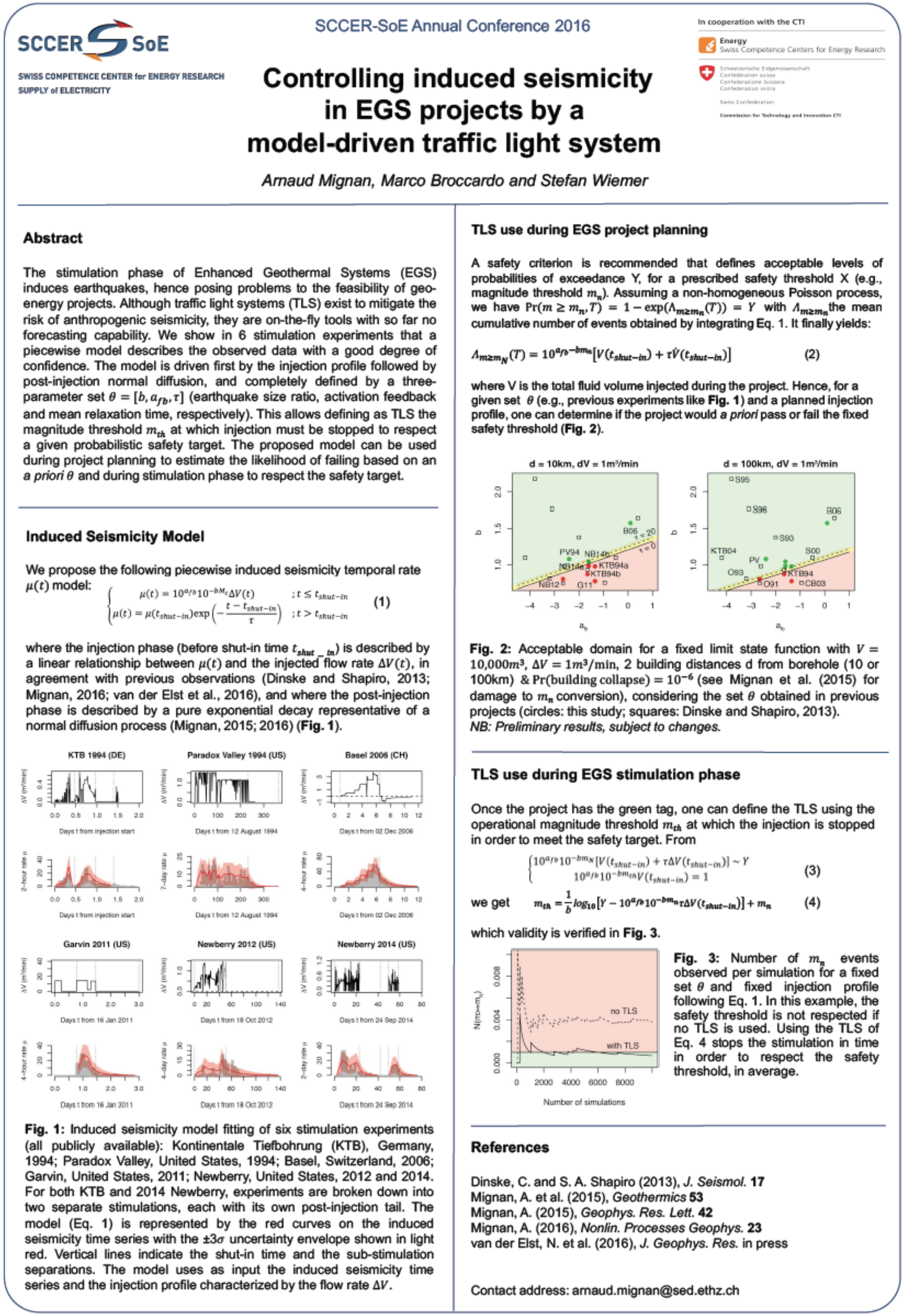
10) "Induced seismicity risk analysis in OpenQuake. Basel case, validation and GIS integration", by Marco Broccardo, Laurentiu Danciu, Arnaud Mignan, Stefan Wiemer

11) "Impact of combined wind and solar energy on the Swiss electricity system", by Jérôme Dujardin, Annelen Kahl, Bert Kruyt, Michael Lehning

12) "Seasonal and Diurnal Wind Power", by Bert Kruyt and Michael Lehning

13) "Nonstructural Damage Tests on Masonry Building Walls: First Phase", by Max Didier, Marco Broccardo, Giuseppe Abbiati, Christoph Jost, Laurentiu Danciu, Bozidar Stojadinovic, Domenico Giardini

14) "Accounting for uncertainty in the propagation of dam break flood waves in the Rhone River: from hazards to risks", by A. Darcourt, J. P. Matos and A. J. Schleiss



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SCCER-SoE Annual Conference 2016

In cooperation with the CTI – Energy Swiss Competence Centers for Energy Research – Commission for Technology and Innovation CTI

Controlling induced seismicity in EGS projects by a model-driven traffic light system

Arnaud Mignan, Marco Broccardo and Stefan Wiemer

Abstract

The stimulation phase of Enhanced Geothermal Systems (EGS) induces earthquakes, hence posing problems to the feasibility of geo-energy projects. Although traffic light systems (TLS) exist to mitigate the risk of anthropogenic seismicity, they are on-the-fly tools with so far no forecasting capability. We show in 6 stimulation experiments that a piecewise model describes the observed data with a good degree of confidence. The model is driven first by the injection profile followed by post-injection normal diffusion, and completely defined by a three-parameter set $\theta = [b, a_{fb}, \tau]$ (earthquake size ratio, activation feedback and mean relaxation time, respectively). This allows defining as TLS the magnitude threshold m_{th} at which injection must be stopped to respect a given probabilistic safety target. The proposed model can be used during project planning to estimate the likelihood of failing based on an *a priori* θ and during stimulation phase to respect the safety target.

Induced Seismicity Model

We propose the following piecewise induced seismicity temporal rate $\mu(t)$ model:

$$\begin{cases} \mu(t) = 10^{a_{fb}} 10^{-bM_c} \Delta V(t) & ; t \le t_{shut-in} \\ \mu(t) = \mu(t_{shut-in}) \exp\left(-\frac{t - t_{shut-in}}{\tau}\right) & ; t > t_{shut-in} \end{cases} \quad (1)$$

where the injection phase (before shut-in time $t_{shut-in}$) is described by a linear relationship between $\mu(t)$ and the injected flow rate $\Delta V(t)$, in agreement with previous observations (Dinske and Shapiro, 2013; Mignan, 2016; van der Elst et al., 2016), and where the post-injection phase is described by a pure exponential decay representative of a normal diffusion process (Mignan, 2015; 2016) (**Fig. 1**).

Fig. 1: Induced seismicity model fitting of six stimulation experiments (all publicly available): Kontinentale Tiefbohrung (KTB), Germany, 1994; Paradox Valley, United States, 1994; Basel, Switzerland, 2006; Garvin, United States, 2011; Newberry, United States, 2012 and 2014. For both KTB and 2014 Newberry, experiments are broken down into two separate stimulations, each with its own post-injection tail. The model (Eq. 1) is represented by the red curves on the induced seismicity time series with the ±3σ uncertainty envelope shown in light red. Vertical lines indicate the shut-in time and the sub-stimulation separations. The model uses as input the induced seismicity time series and the injection profile characterized by the flow rate ΔV.

TLS use during EGS project planning

A safety criterion is recommended that defines acceptable levels of probabilities of exceedance Y, for a prescribed safety threshold X (e.g., magnitude threshold m_N). Assuming a non-homogeneous Poisson process, we have $\Pr(m \ge m_N, T) = 1 - \exp(\Lambda_{m \ge m_N}(T)) = Y$ with $\Lambda_{m \ge m_N}$ the mean cumulative number of events obtained by integrating Eq. 1. It finally yields:

$$\Lambda_{m \ge m_N}(T) = 10^{a_{fb} - bm_N}[V(t_{shut-in}) + \tau \dot{V}(t_{shut-in})] \quad (2)$$

where V is the total fluid volume injected during the project. Hence, for a given set θ (e.g., previous experiments like **Fig. 1**) and a planned injection profile, one can determine if the project would *a priori* pass or fail the fixed safety threshold (**Fig. 2**).

Fig. 2: Acceptable domain for a fixed limit state function with $V = 10{,}000 m^3$, $\Delta V = 1 m^3/min$, 2 building distances d from borehole (10 or 100km) & $\Pr(\text{building collapse}) = 10^{-6}$ (see Mignan et al. (2015) for damage to m_N conversion), considering the set θ obtained in previous projects (circles: this study; squares: Dinske and Shapiro, 2013).
NB: Preliminary results, subject to changes.

TLS use during EGS stimulation phase

Once the project has the green tag, one can define the TLS using the operational magnitude threshold m_{th} at which the injection is stopped in order to meet the safety target. From

$$\begin{cases} 10^{a_{fb}} 10^{-bm_N}[V(t_{shut-in}) + \tau \Delta V(t_{shut-in})] \sim Y \\ 10^{a_{fb}} 10^{-bm_{th}} V(t_{shut-in}) = 1 \end{cases} \quad (3)$$

we get $m_{th} = \frac{1}{b} \log_{10}[Y - 10^{a_{fb}} 10^{-bm_N} \tau \Delta V(t_{shut-in})] + m_N$ (4)

which validity is verified in **Fig. 3**.

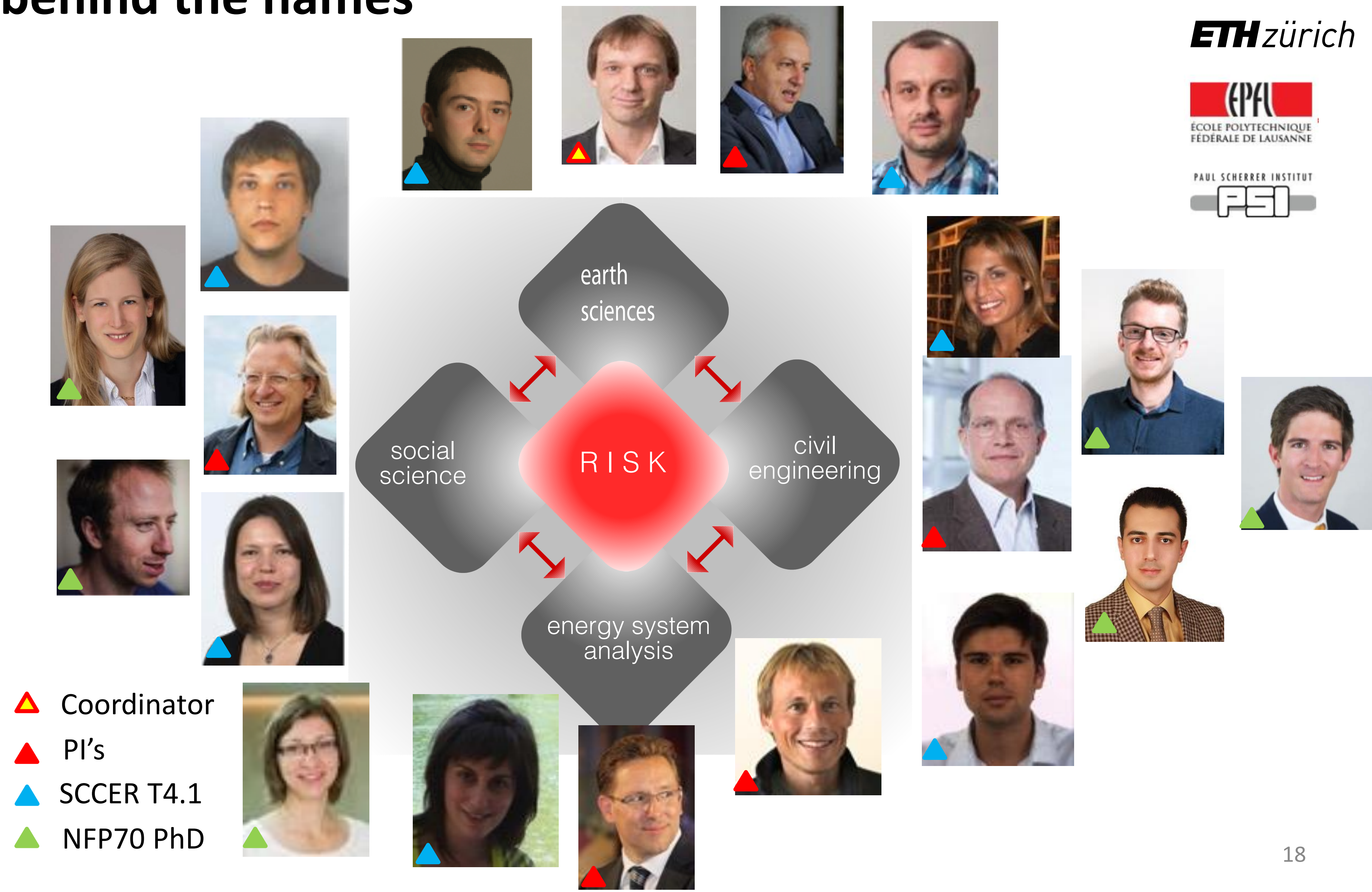
Fig. 3: Number of m_N events observed per simulation for a fixed set θ and fixed injection profile following Eq. 1. In this example, the safety threshold is not respected if no TLS is used. Using the TLS of Eq. 4 stops the stimulation in time in order to respect the safety threshold, in average.

References

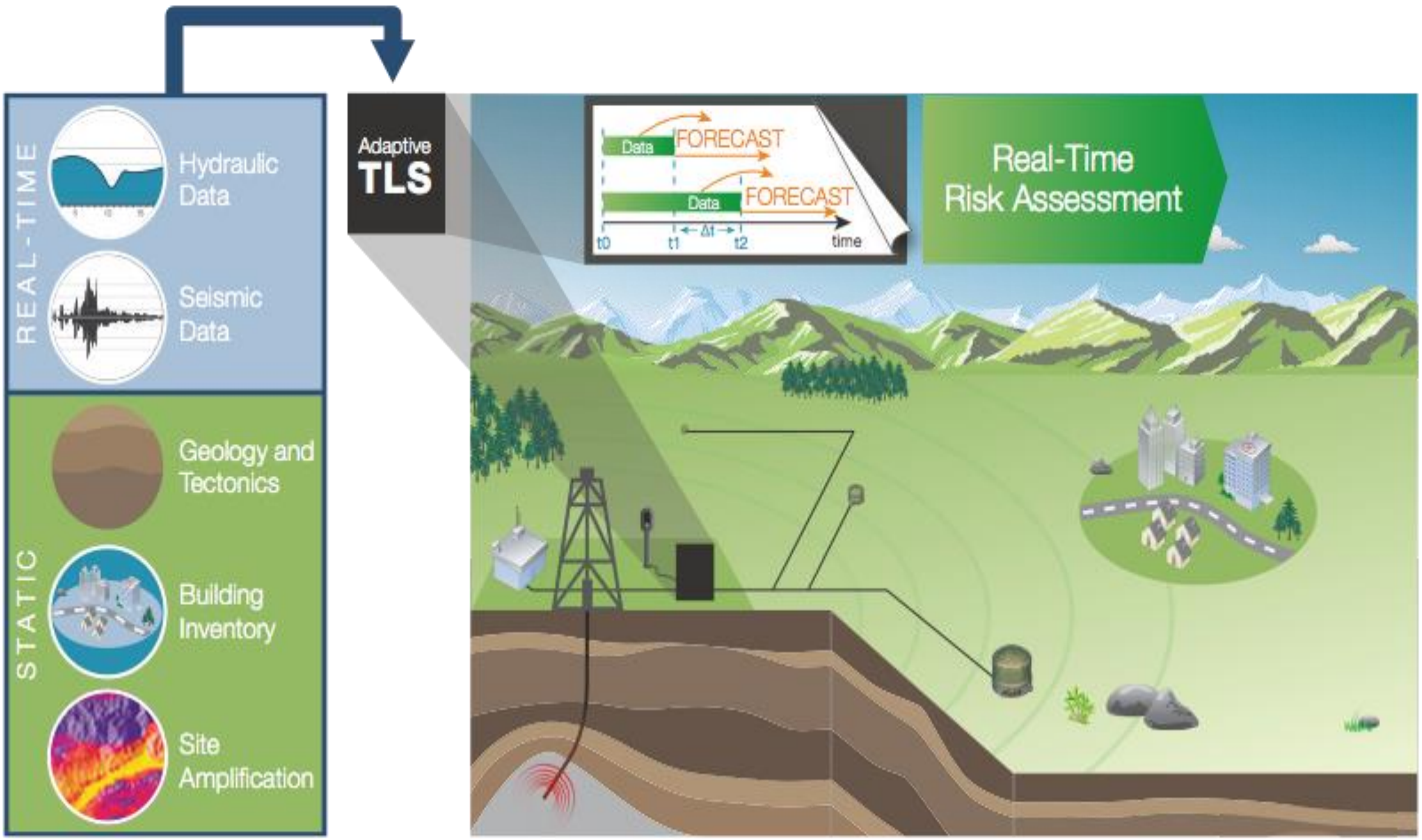
Dinske, C. and S. A. Shapiro (2013), *J. Seismol.* **17**
Mignan, A. et al. (2015), *Geothermics* **53**
Mignan, A. (2015), *Geophys. Res. Lett.* **42**
Mignan, A. (2016), *Nonlin. Processes Geophys.* **23**
van der Elst, N. et al. (2016), *J. Geophys. Res.* in press

Contact address: arnaud.mignan@sed.ethz.ch

And an some of the faces behind the names



Our vison: Smarter systems for managing Induced Seismicity



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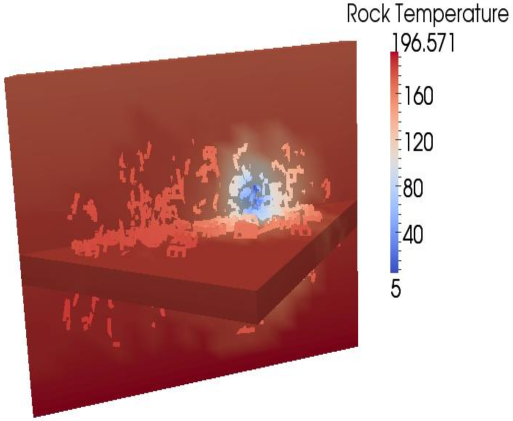
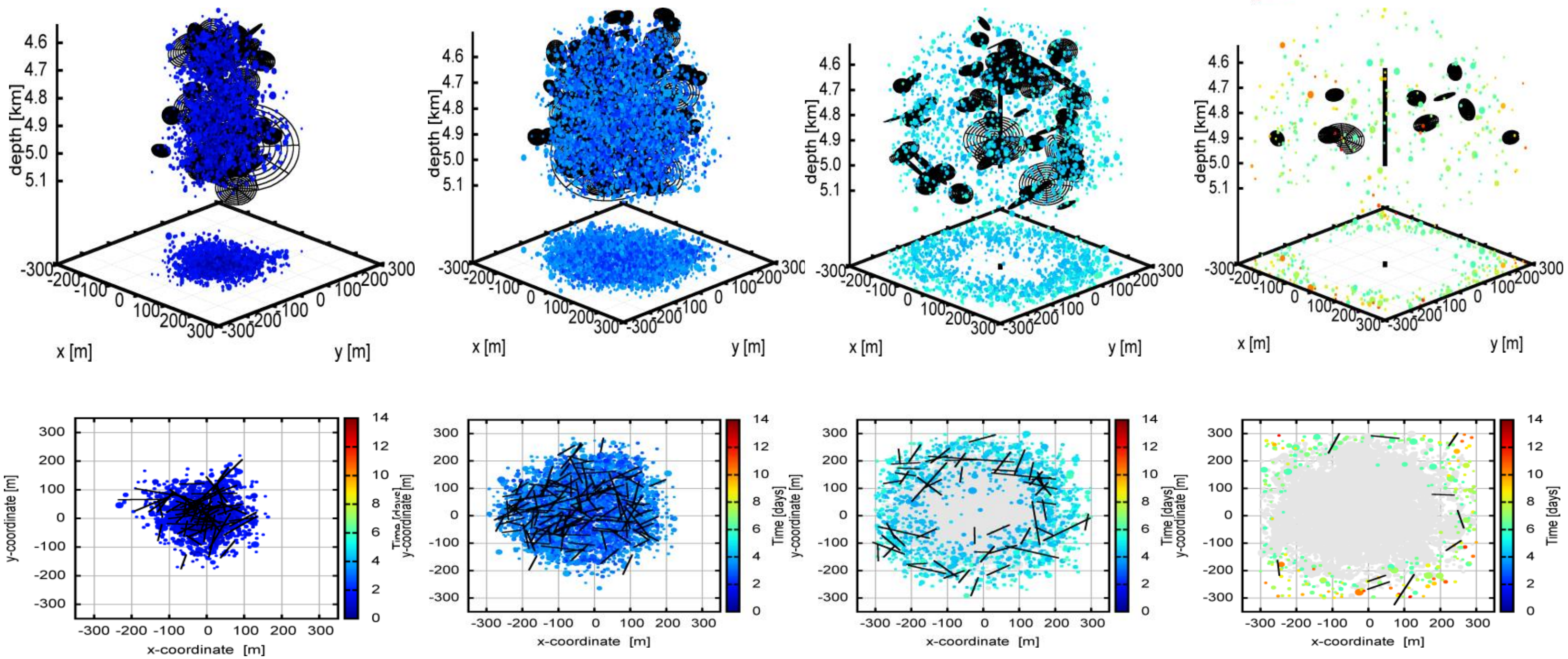
(Selected) ongoing activities (1)

- Numerical Model development for understanding and forecasting the coupled problem of permeability creation ← → seismicity evolution.





0-2 days *2-4 days* *4-6 days* *6-14 days*

(Selected) ongoing activities (1)

The importance of earthquake interactions for injection-induced seismicity: Retrospective modeling of the Basel Enhanced Geothermal System

Article *in* Geophysical Research Letters 43(10) · May 2016
DOI: 10.1002/2016GL068932

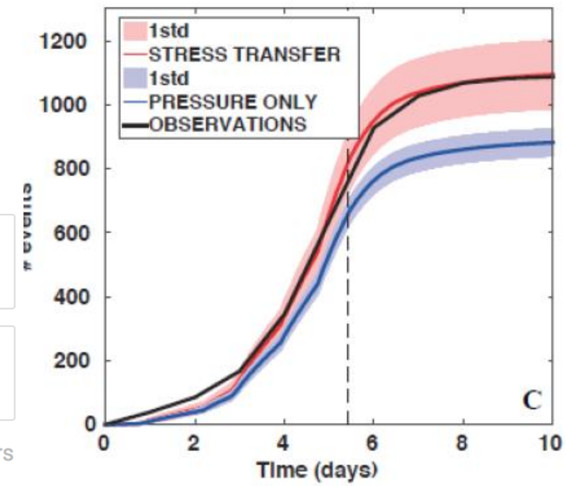
1st Flaminia Catalli
19.12 · Helmholtz-Zentrum Potsdam - Deutsc...

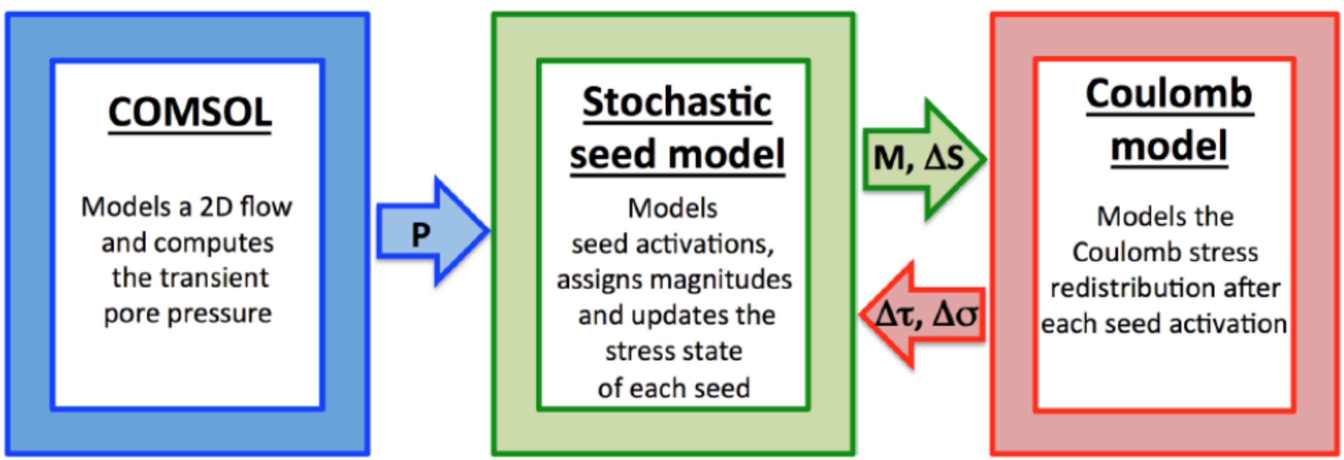
2nd Antonio Pio Rinaldi
24.17 · ETH Zurich

3rd Valentin Gischig
24.83 · ETH Zurich

+ 1

Last Stefan Wiemer
39.13 · ETH Zurich





NC PAST Postulate also explains linear relationship μ≈ΔV & parabolic spatial front

Nonlin. Processes Geophys., 23, 107–113, 2016
www.nonlin-processes-geophys.net/23/107/2016/
doi:10.5194/npg-23-107-2016

Nonlinear Processes in Geophysics
Open Access

Static behaviour of induced seismicity

Arnaud Mignan
Institute of Geophysics, ETH Zurich, Zurich, Switzerland

with t_0 being the starting time of the injection. The volume change rate is then defined as

$$\Delta V(t, \Delta t) = \frac{V(t) - V(t - \Delta t)}{\Delta t}, \quad (8)$$

with Δt being a time increment.

In the EGS case, $r \cong h$, with h being the borehole depth and induced seismicity defined as hypocentres. The spatio-temporal stress field $\sigma(r,t)$ becomes

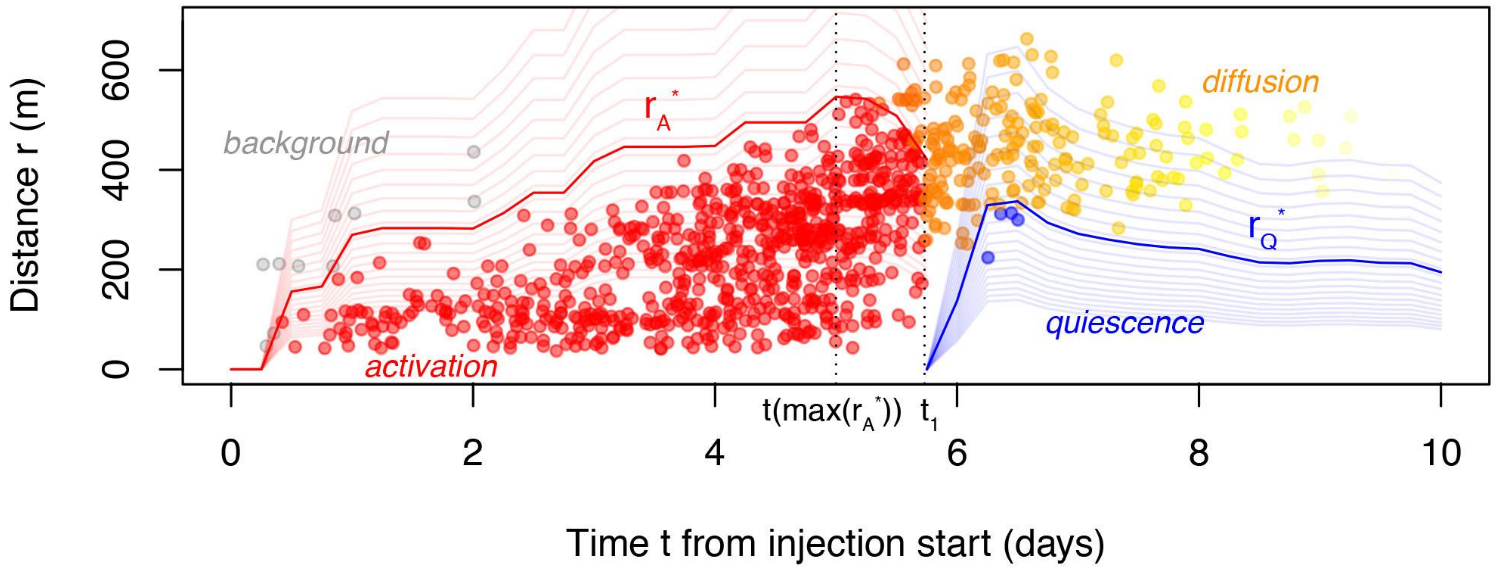
$$\sigma(r,t) = \begin{cases} \sigma_0^*, & t < t_0 \\ \frac{r_0^n}{(r+r_0)^n} P(t, r=0) + \sigma_0^*, & t \geq t_0 \end{cases} \quad (9)$$

with r being the distance along the stress field gradient from ... usion exponent for static ... l radius of volume $V_0 =$ ... t. The parameter r_0 is in- ... ced seismicity case (see ... case when fluids are in- ... re ejected (bleed-off), or, ... hen the pressure change ... ative, respectively. It fol-

$$\ldots V(t)\Big)^{1/n} - r_0 \quad (10)$$
$$\ldots \Delta V(t)\Big)^{1/n} - r_0,$$

... nporal shape of the in- ... s on the nth root of the flow rate profile $Q(t)$ (with $n = 3$ in the static stress case). This parabolic relationship is similar to the generalised form $r(t) \propto m(t)^{1/d}$ derived from non-linear poroelasticity in a ...

with k being a geometric parameter and d the spatial dimension. For the tectonic case in which $r_{max} \gg h$, the volume is assumed to be a cylinder with $k = \pi$, $d = 2$, and δ being the density of epicentres in space (Fig. 1c). It should ...



power law behaviour observed prior to some large mainshocks (Fig. 1d) (see the review by Sammis and Sornette (2002) for different physical processes yielding a temporal power law).

(Selected) ongoing activities (2)

- Model verification/calibration/validation experiments. Benchmarking, ensemble models etc.

Validating induced seismicity forecast models - Induced Seismicity Test Bench: INDUCED SEISMICITY TEST BENCH

Article *in* Journal of Geophysical Research: Solid Earth · August 2016
DOI: 10.1002/2016JB013236

1st Eszter Kiraly
13.63 · ETH Zurich

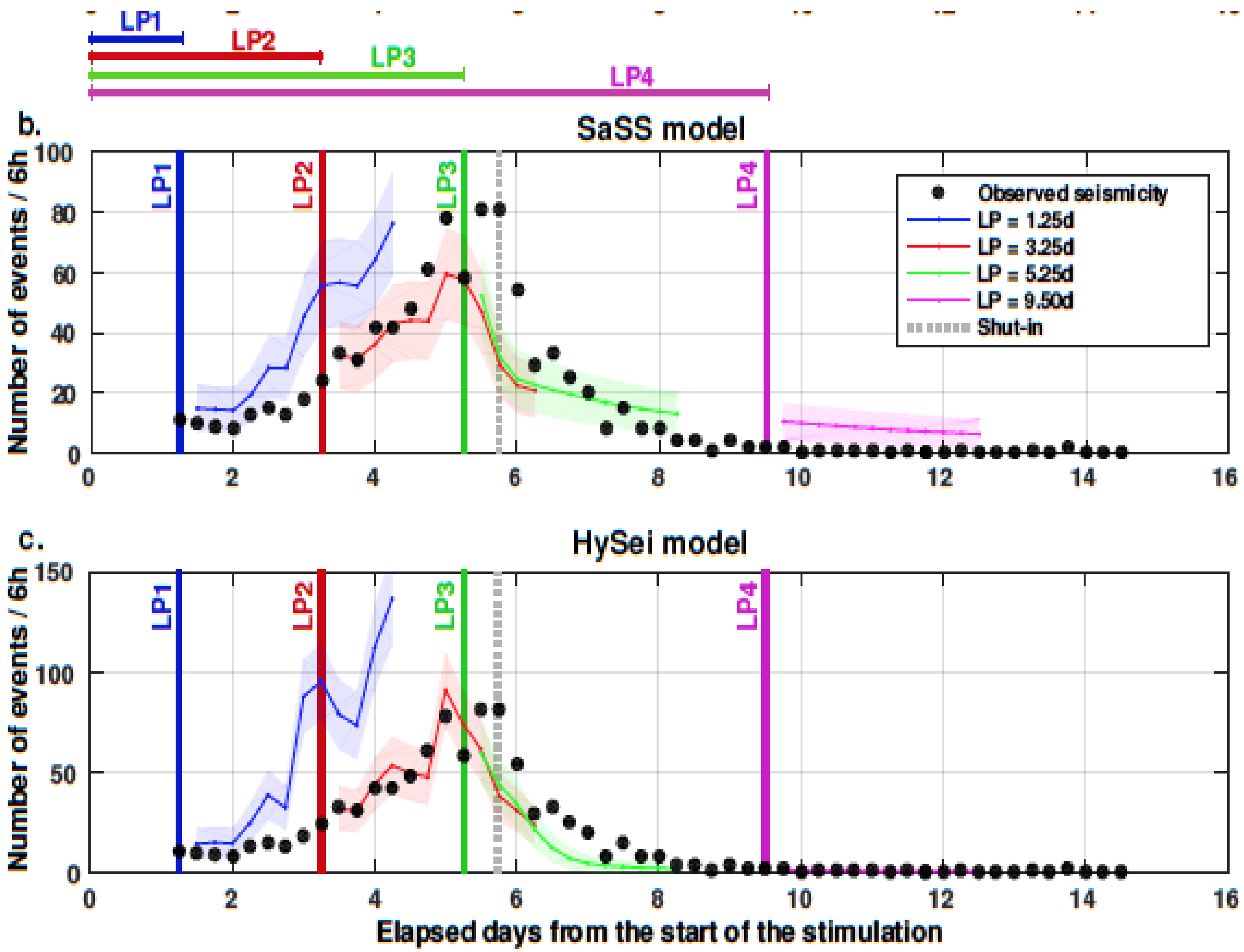
2nd J. Douglas Zechar

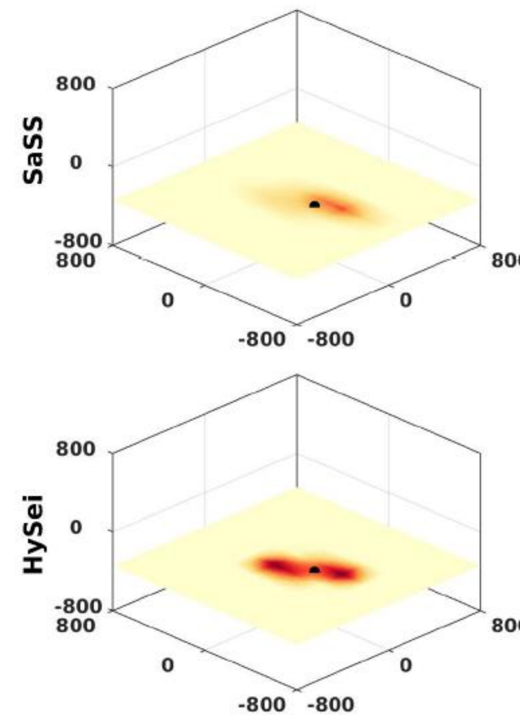
3rd Valentin Gischig
24.83 · ETH Zurich

+ 2

Last Joseph Doetsch
26.51 · ETH Zurich

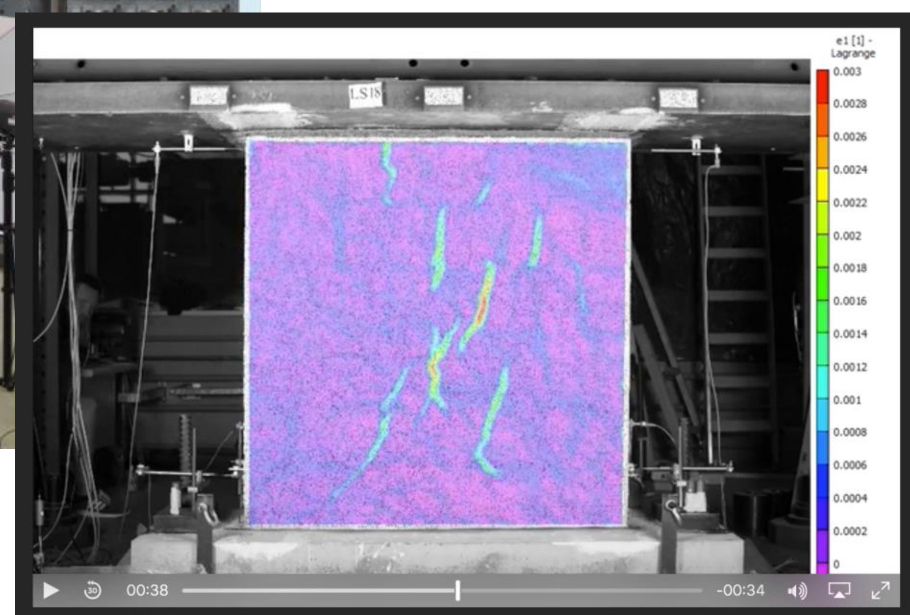
(Selected) ongoing activities (2)





(Selected) ongoing activities (3)

- Understanding cracks in buildings using experiments



http://www.seismo.ethz.ch/static/sccer-soe/videos/sources/wall_test.mp4

Individual and societal risk metrics as parts of a risk governance framework for induce seismicity

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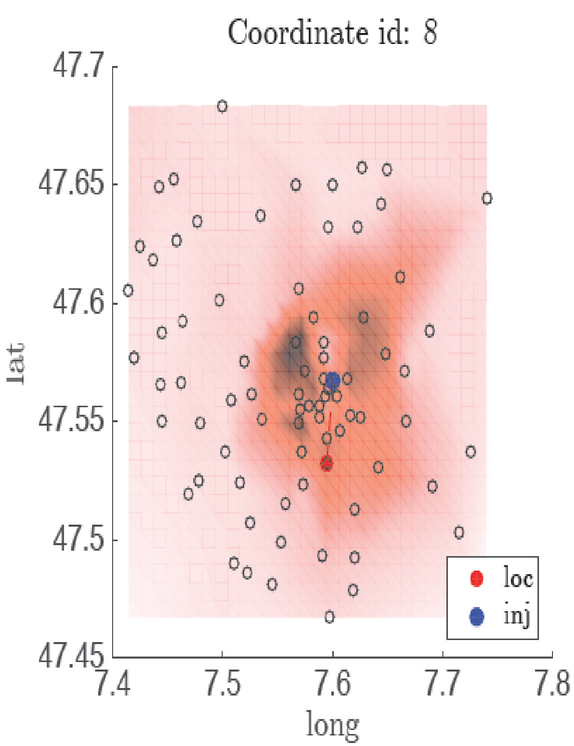
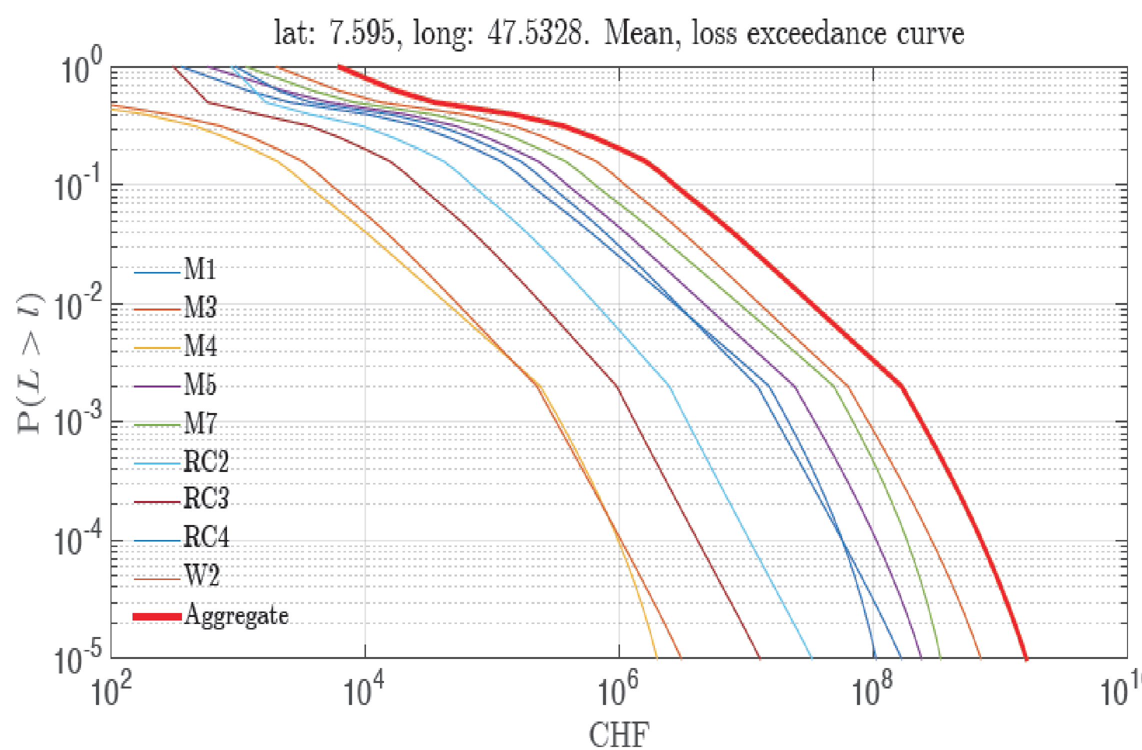
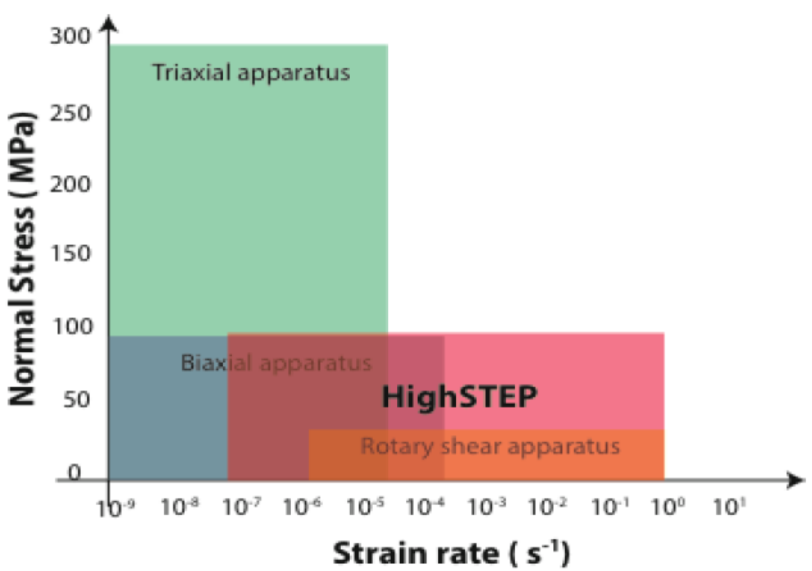
[(2,5)] *Swiss Seismological Service, SED, ETH Zürich*
[(3)] *Institute of Geophysics, ETH Zürich*
[(1,4)] *Chair of Structural Dynamics & Earthquake Engineering, ETH Zürich*



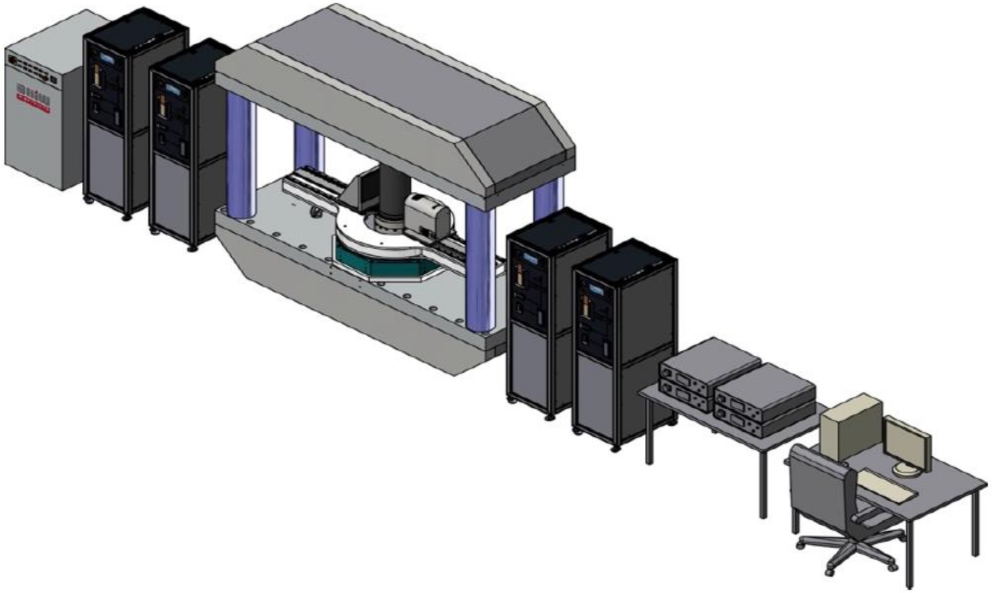


(Selected) ongoing activities (4)

- **Lab-scale experiments to study earthquake physics**
  - **HighSTEP, a machine jointly owned by ETH and EPFL** now being built at EPFL (Marie Violay/Claudio Madonna).
  - **LabQuake** triaxial apparatus for ETH (Rock Def Lab) request from SNF R'Equip.

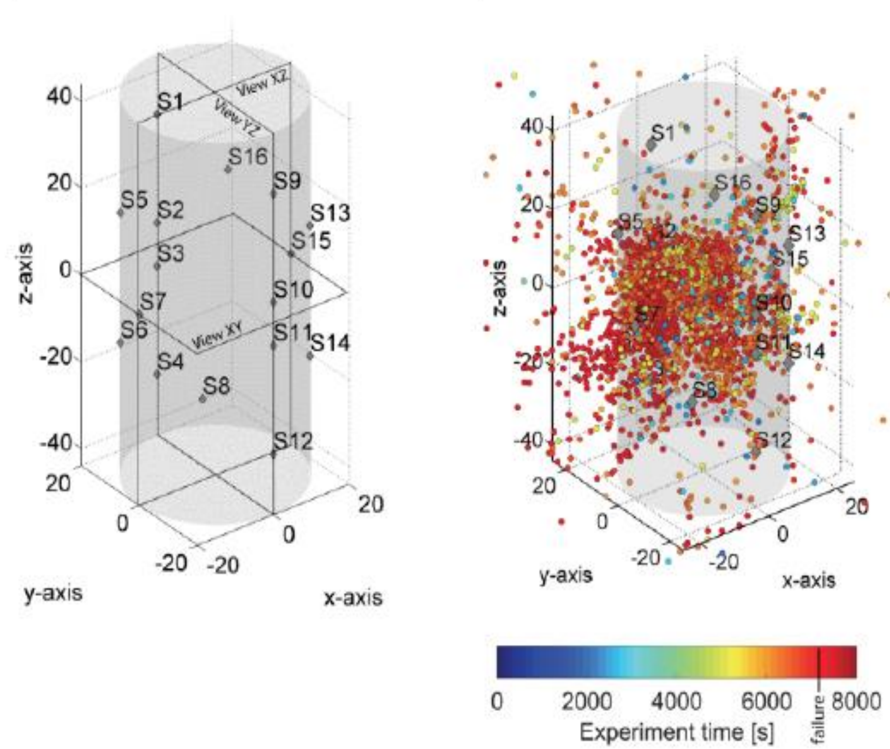


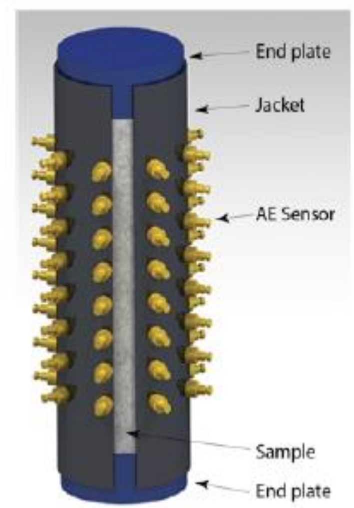
(Selected) ongoing activities (4)



a)

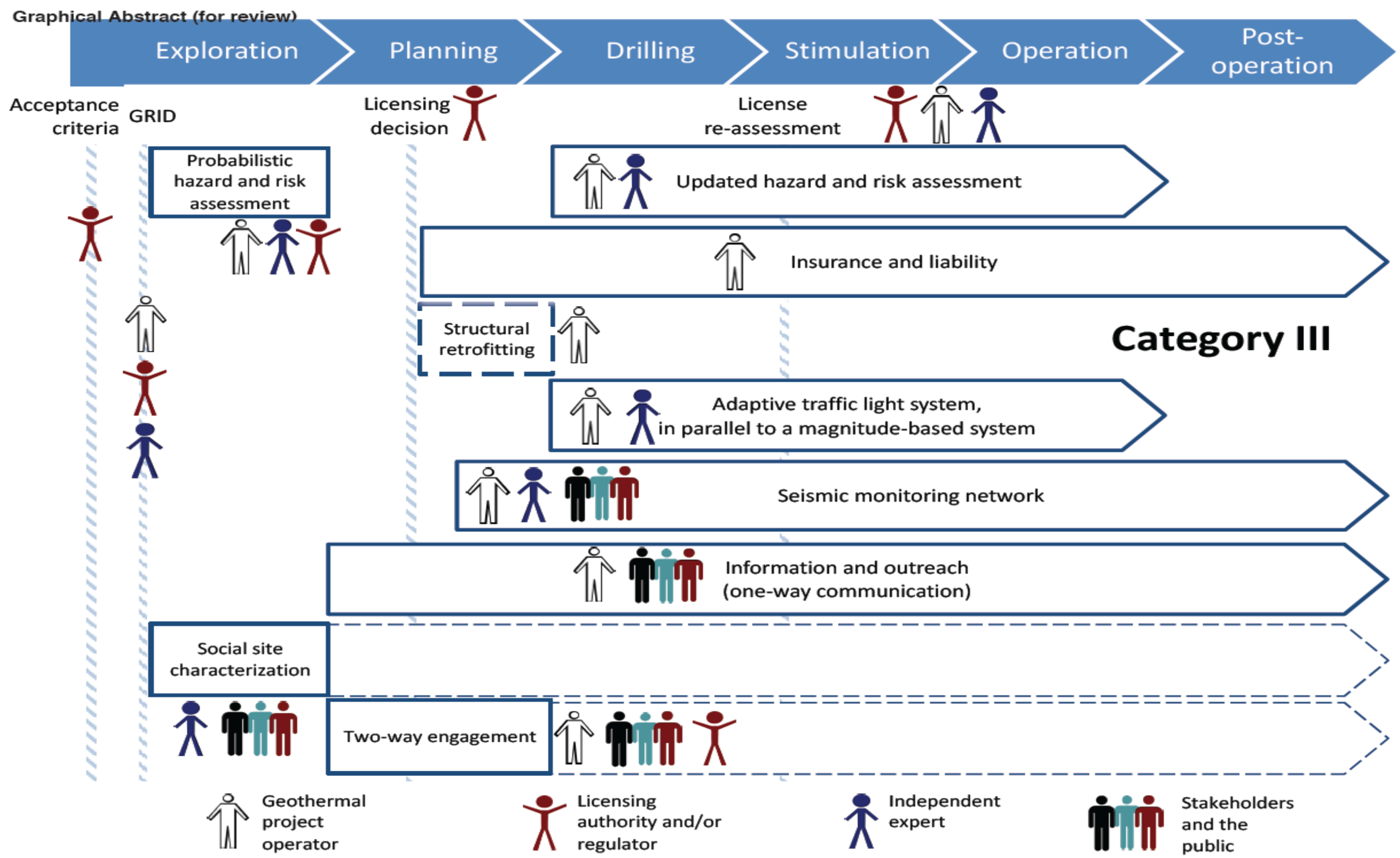
b)



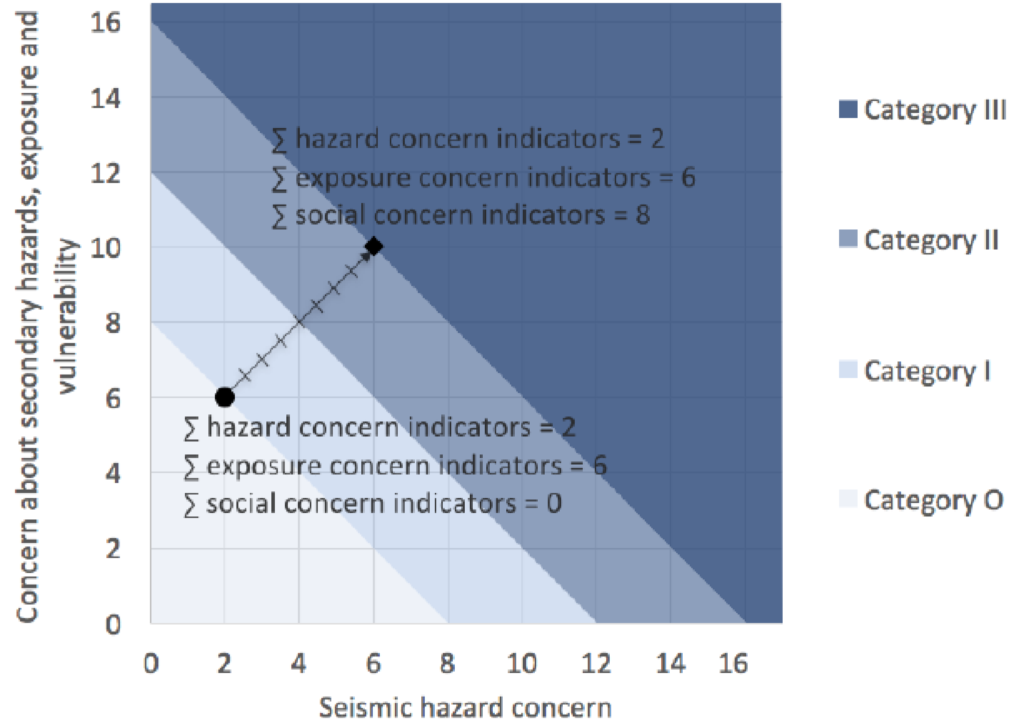


(Selected) ongoing activities (5)

- Tailor made risk governance for Switzerland



(Selected) ongoing activities (5)



Tailor-made risk governance for induced seismicity of geothermal energy projects: An application to Switzerland

Author: Evelina Trutnevyte[1,3]*, Stefan Wiemer[2,3]
* Corresponding author, evelina.trutnevyte@alumni.ethz.ch, phone +41 44 633 87 05

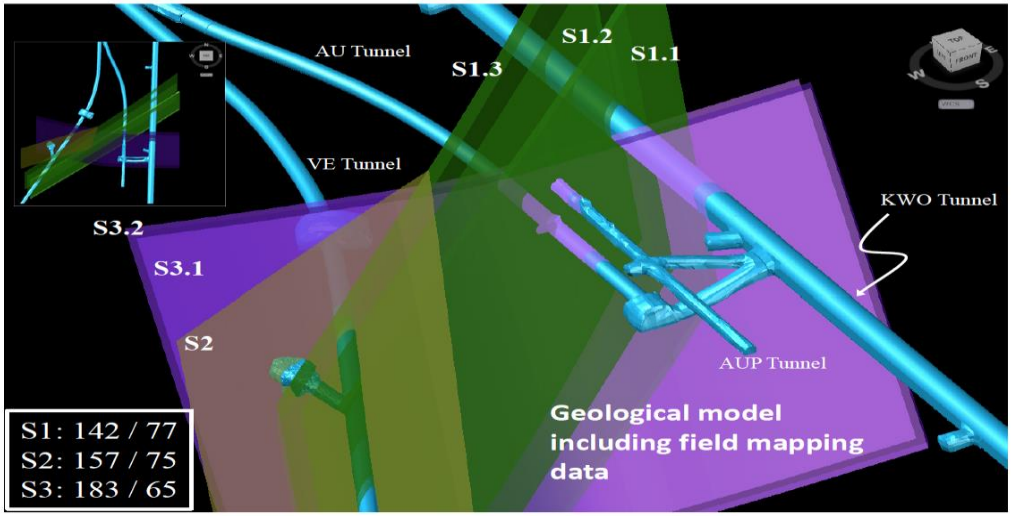
[1] ETH Zurich, Department of Environmental Systems Science (D-USYS), USYS Transdisciplinarity Laboratory, Universitätstrasse 16, 8092 Zurich, Switzerland

[2] ETH Zurich, Swiss Seismological Service, Sonneggstrasse 5, 8092 Zurich, Switzerland

[3] Swiss Competence Center for Energy Research – Supply of Electricity, Sonneggstrasse 5, 8092 Zurich, Switzerland

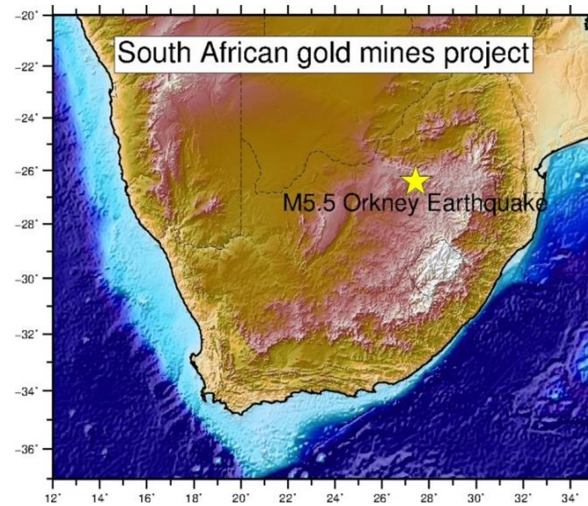
(Selected) ongoing activities (6): Grimsel

- A great collaborative effort.
- A chance to study fundamental science questions – including induced seismicity.



International Continental Drilling Programme (ICDP): DSEIS

- Deep gold mines actively progressing (> 3 km) offer an interesting very high strain rate environment to study earthquakes and faulting.
- We are part of an international ICDP team to investigate processes related to natural and anthropogenic earthquakes (just funded at 1 Mio. $)



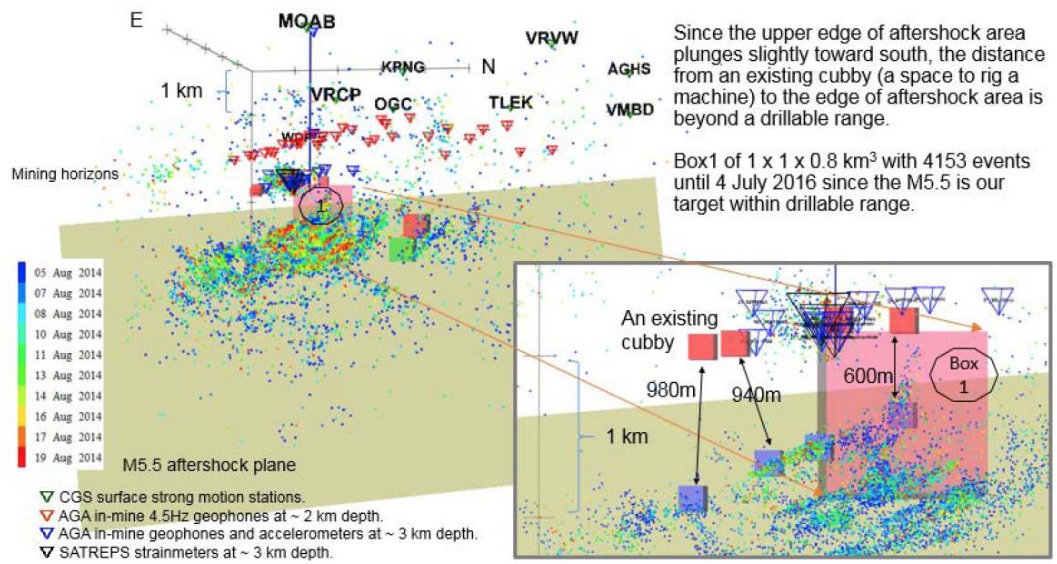


Figure 1. Seismicity in a 14-day period following the M5.5. Box 1 is a drilling target at **MK** within a drillable range. First, we have to identify a geological structure responsible for the 2014 M5.5 and calibrate the seismic velocity to refine seismicity location. The 2nd hole will be dedicated to geomicrobiology research.

www.seismo.ethz.ch

GEOBEST-CH

- Support cantons in all matters related to geothermal projects (monitoring, hazard and risk assessment, best practice etc.).
- First workshop with cantonal authorities: spring 2016.

Mit Unterstützung von energieschweiz

Unser Engagement: unsere Zukunft.

DESTRESS

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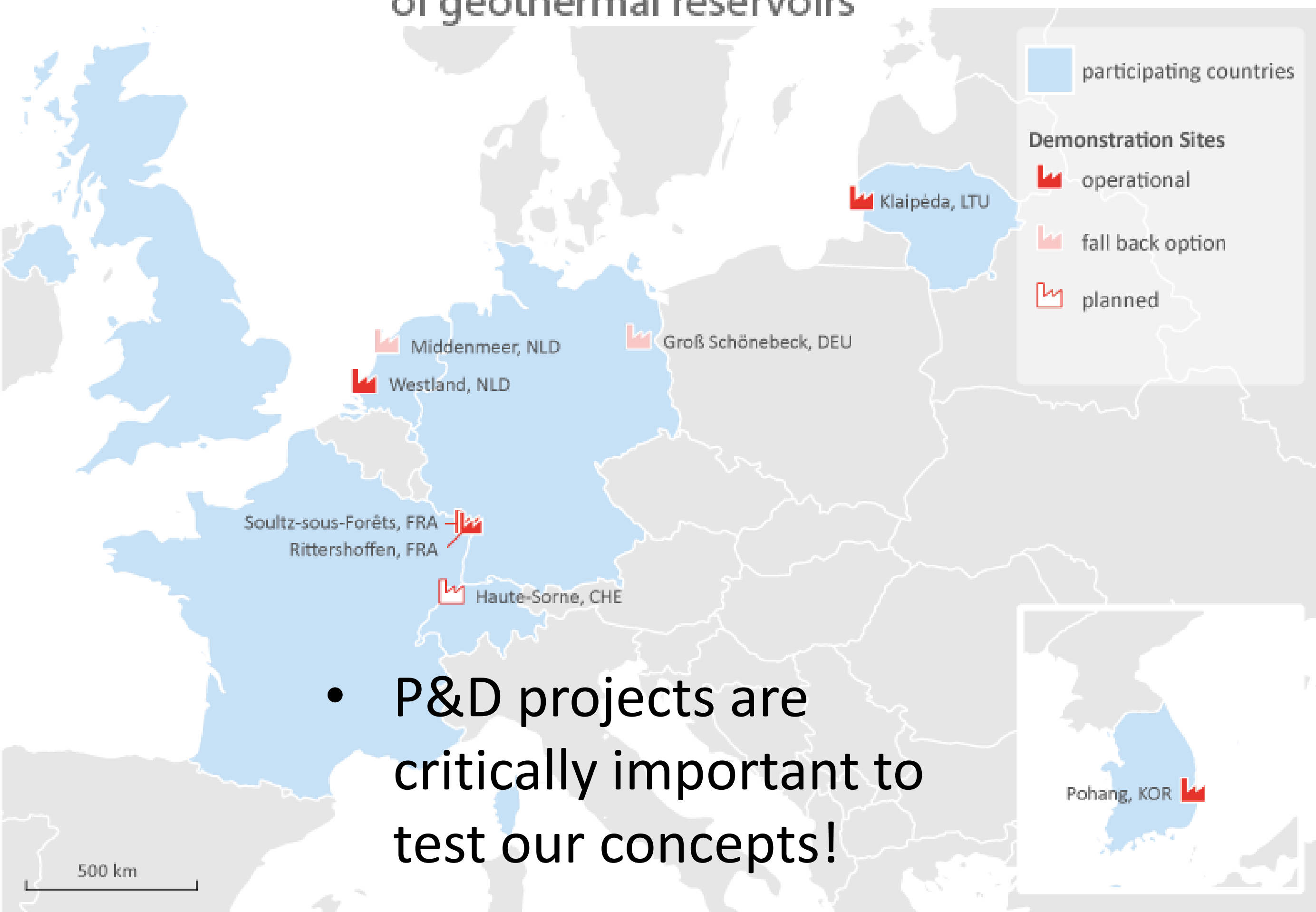
Demonstration of soft stimulation treatments of geothermal reservoirs



- P&D projects are critically important to test our concepts!

www.destress-h2020.eu

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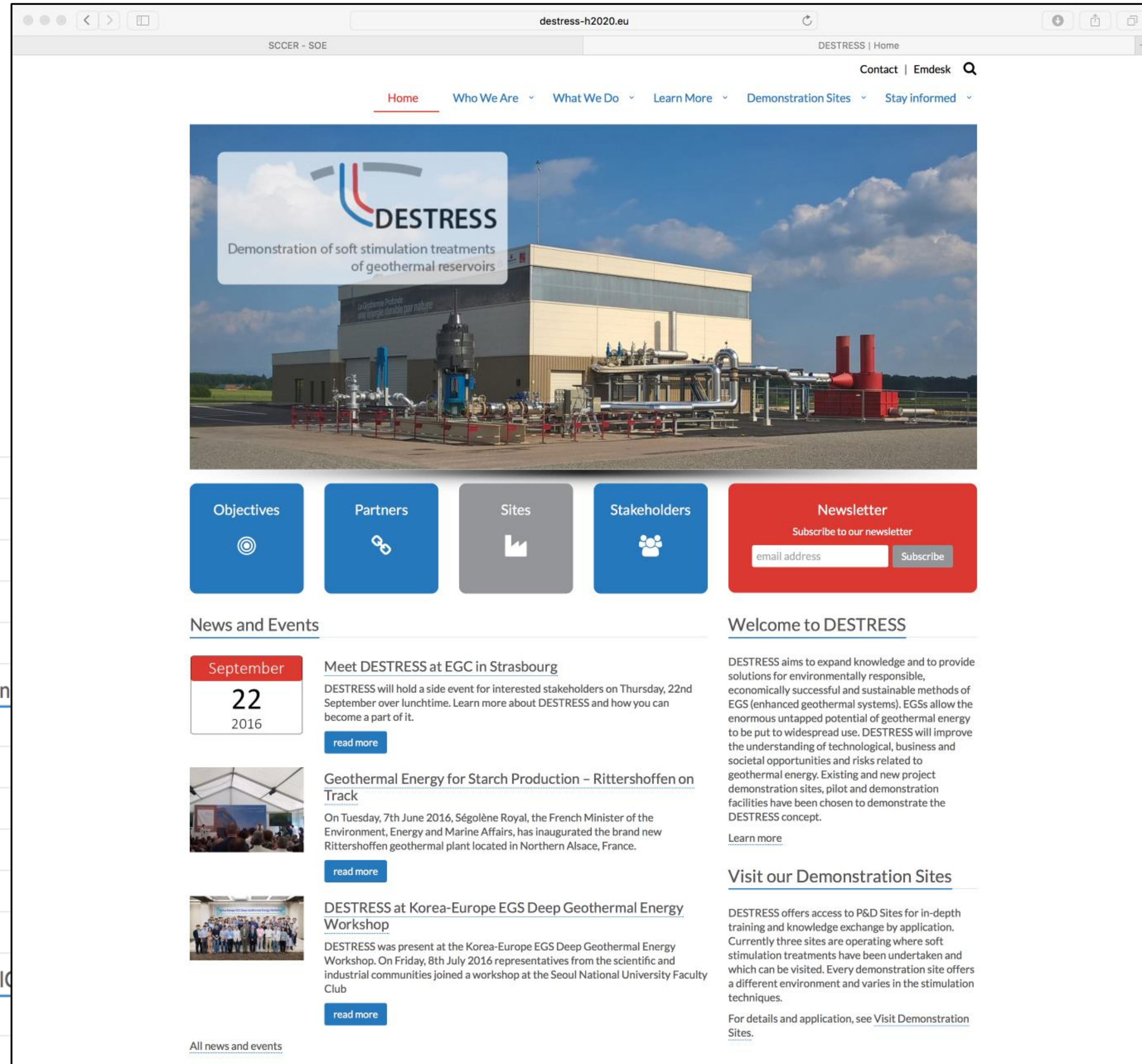

Helmholtz Zentrum Potsdam (GFZ), Germany

Energie Baden-Württemberg AG (EnBW), Germany

és-Géothermie (ESG), France

University of Glasgow, United Kingdom

Geo-Energie Suisse AG, Switzerland

TNO, The Netherlands

Eidgenössische Technische Hochschule Zürich (ETH), Switzerlan

Geothermie Neubrandenburg GmbH (GTN), Germany

Geoterma UAB, Lithuania

Université de Strasbourg, France

Delft University of Technology (TU Delft), The Netherlands

NexGeo Incorporated, Korea

Seoul National University (SNU), Korea

Korea Institute of Civil Engineering and Building Technology (KI

ECW Geomanagement BV (ECW), The Netherlands

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Schatzalp workshop 2017

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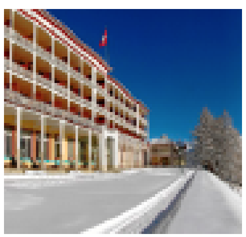
Office fédéral de l'énergie OFEN
Ufficio federale dell'energia UFE

Thank you!

Focus Topics

The workshop will cover eight thematic areas, each intro
2 to 3 invited keynote speakers, followed by 2 to 3 solicit
There will be a moderated discussion at the end of each
and at the end of the workshop.

- Case Studies
- Modeling of Induced Seismicity
- Scaled Experiments
- Monitoring and Analysis of Induced Seismicity
- Risk Governance, Societal Acceptance and License to
- Industry Projects & Perspective
- Pilot and Demonstration Sites & Future Initiatives



Conference Venue

Davos is located within the beautiful Swiss Alpine mountains of Graubünden. It's a city of culture, sports, and nature. It takes a 2:30 hours train ride from Zurich airport to go to Davos.

The conference venue «Schatzalp» is 300 m above Davos, at an altitude of 1861 m. A cable car takes you there in four minutes from Davos-Platz. The nostalgic Art Nouveau style building with its Belle Époque atmosphere opened its doors in 1900 as a luxury sanatorium. The soul of the house, its architecture, has been preserved in its original form until today. A night-lighted sledge trail down to Davos, and the skiing region Schatzalp-Strela are nearby.