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SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

A multi-scale, multi-disciplinary approach to understanding and managing induced seismicity

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September 30, 2014

In cooperation with the CTI

Energy
Swiss Competence Centers for Energy Research

Schweizerische Eidgenossenschaft
Confédération suisse
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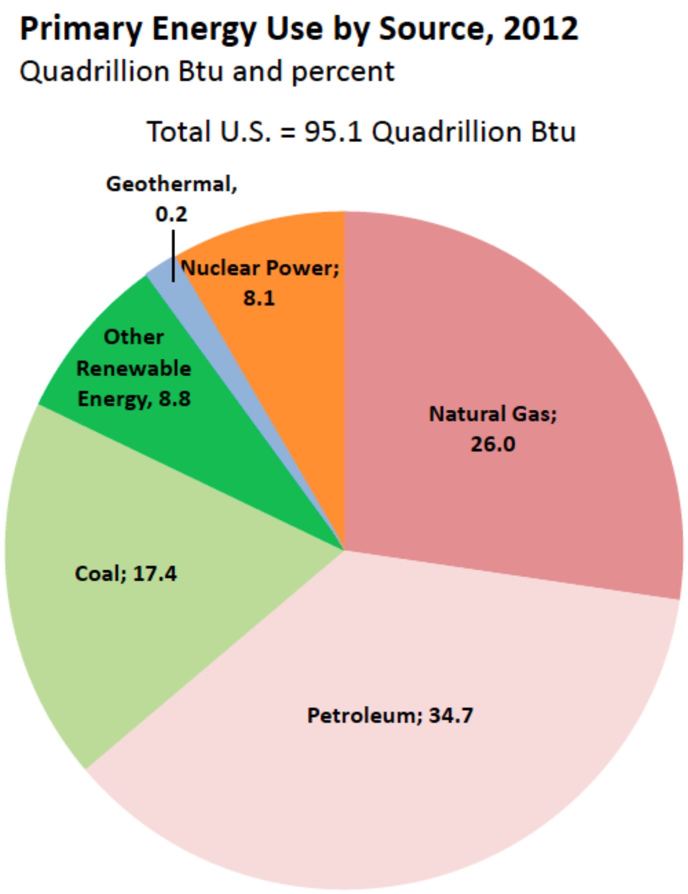
Swiss Confederation

Commission for Technology and Innovation CTI

We all agree: The Subsurface is Critical to our Energy System

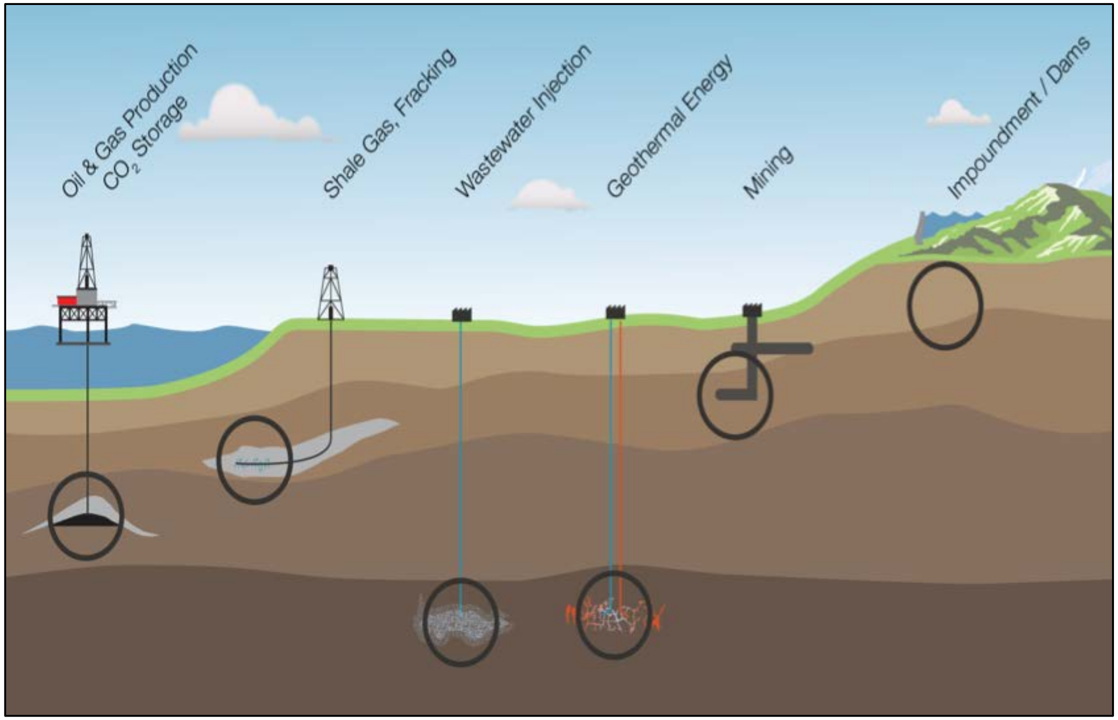
- Subsurface energy sources including coal satisfy over 80% of total U.S. energy needs (EU: Similar)
- The subsurface is a vast CO_2 storage reservoir, as well as for hazardous materials and other energy waste streams.
- The subsurface can also serve as a reservoir for energy storage.
- Large reserves of geothermal energy – but turning reserves into resources requires limiting seismic risk.



EIA, 2012

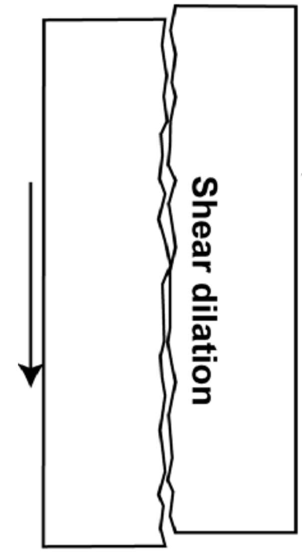
But: Induced seismicity is a growing challenge

- Earthquakes can be **induced** (some say triggered) in many geo-resources applications by a range of physical mechanism.

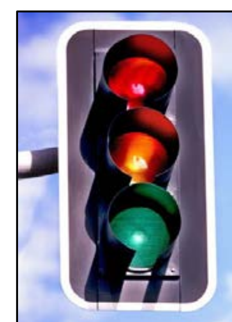


Induced seismicity: A blessing - and a curse

- Induced earthquakes are **the only known mechanism** to create sufficient, permanent permeability in the deep underground for operating a ‘heat exchanger’
- Induced earthquakes are a rich source of information on the evolution and properties of the reservoir.
- Induced earthquakes are at the same time a source of nuisance and concern to the local population and a potential seismic risk.



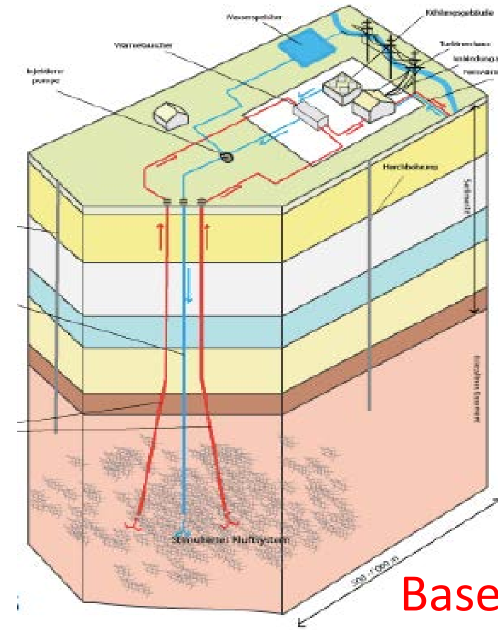
Permeability 100-1000 times higher:



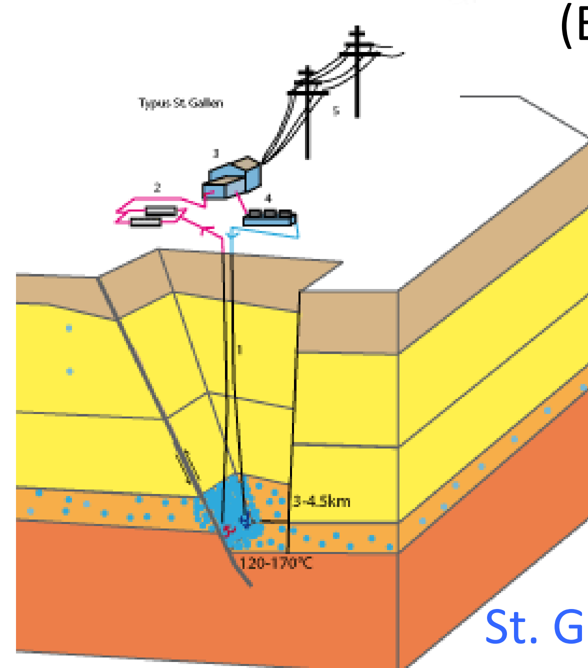
Strangely, tiny Switzerland is often in the frontline when it comes to Deep Geothermal Energy and Induced Earthquakes

- In 2006, **the Basel EGS** project was abruptly terminated after an induced magnitude Ml=3.4 earthquake caused minor damages to hundreds of houses, cumulative paid damages >7Mio CHF.

- In 2013, the **St. Gallen hydrothermal** project induced a magnitude 3.5 during a well-control operation. This event, and the low flow rates, led to the suspension of the DGE project.



Basel Type (EGS)



St. Gallen Type (Hydrothermal)

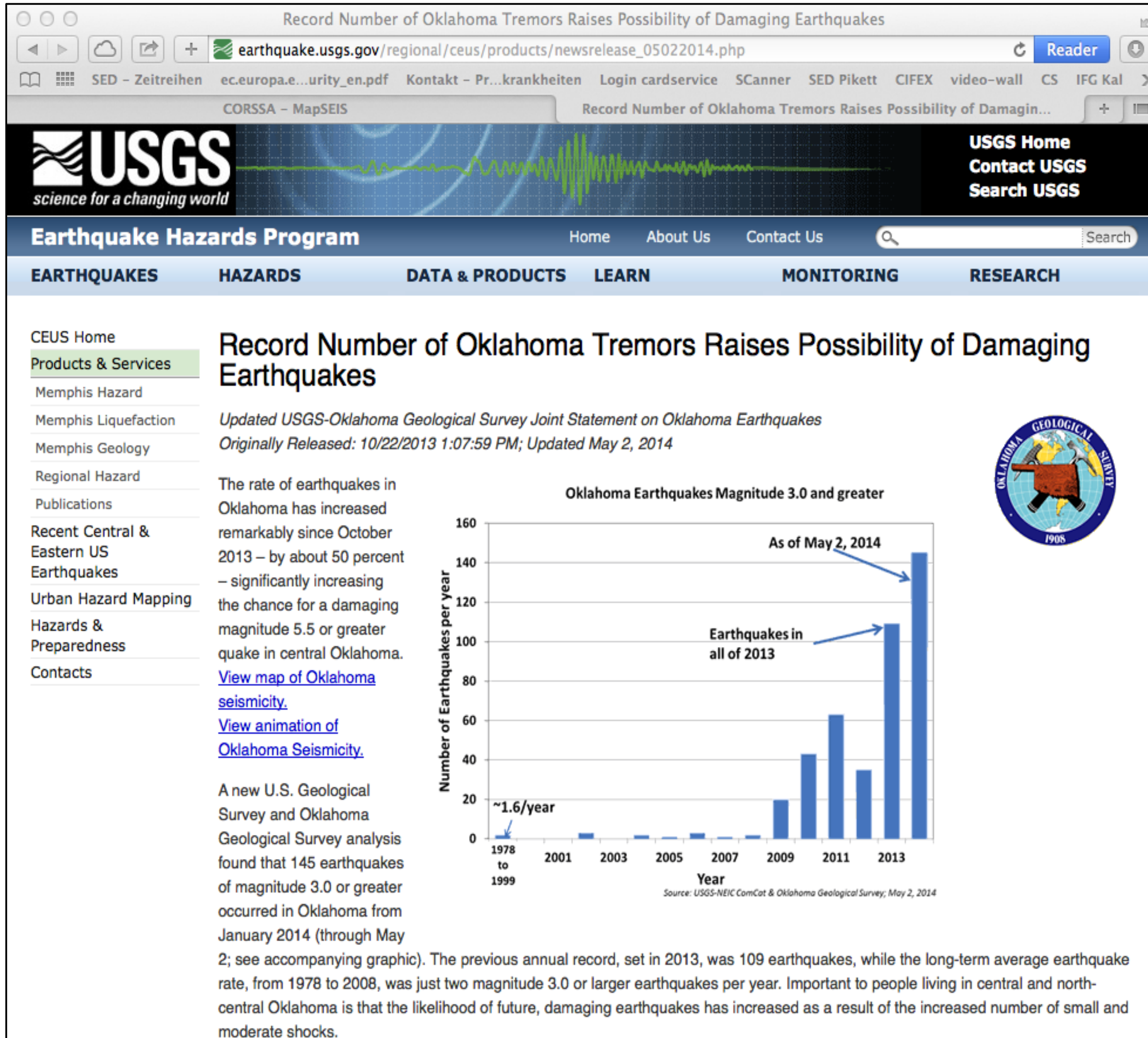
But: A global challenge!

Example 1: Increase of the seismicity in the Eastern US.

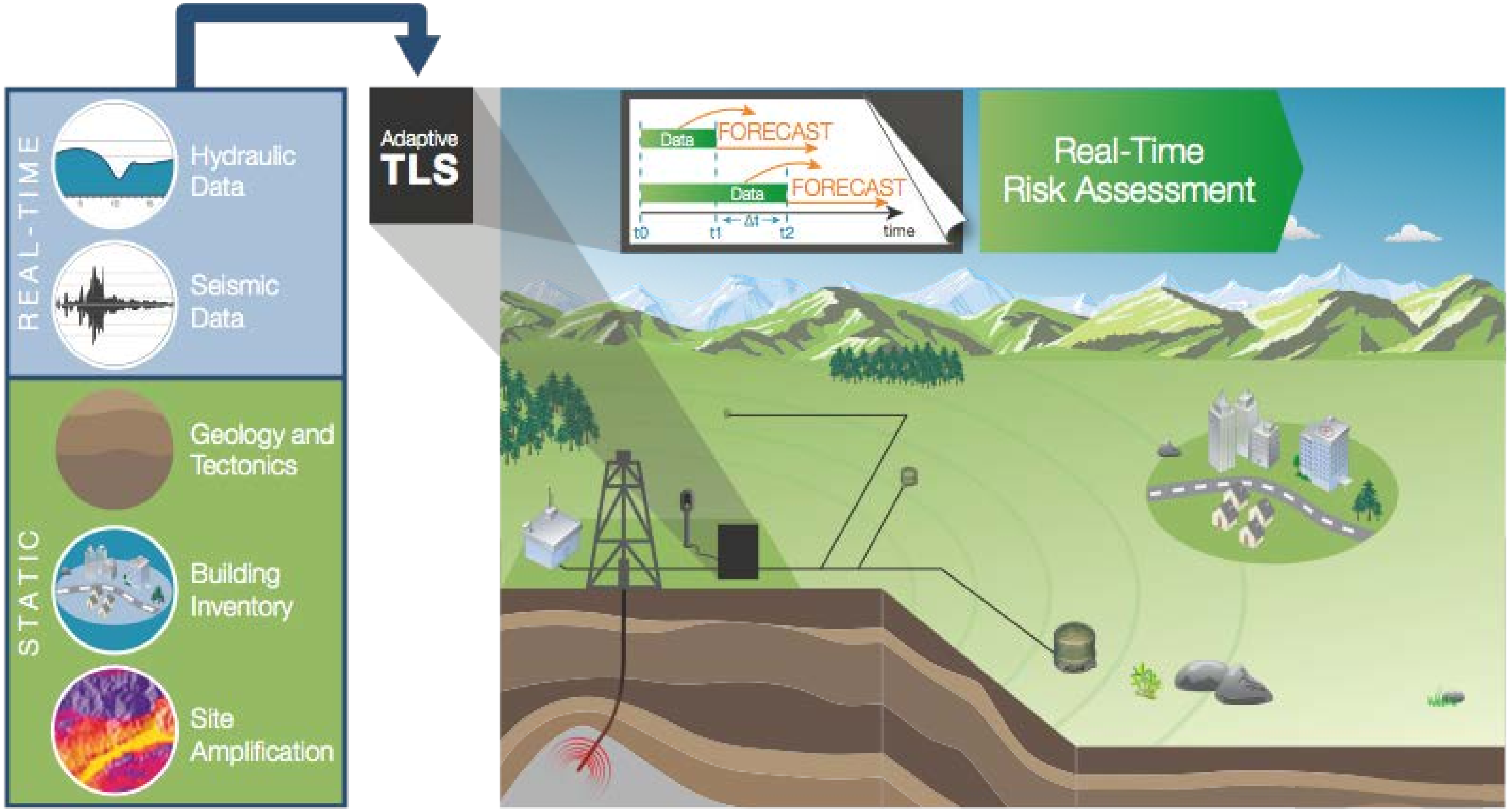
Example 2: Blackpool/Horn River shale gas delays.

Example 3: Groningen gas field.

Footnote: "Deep geothermal energy projects have so far caused no structural damages to buildings nor harmed people"



Here I usually talk about risk governance ... traffic lights etc. ... but even I am tired of it a little ...



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So, let‘s look at the big picture

Q1: Why is *Induced Seismicity* (IS) such a problem to DGE?

H1: It is truly a difficult problem with poorly constrained initial conditions.

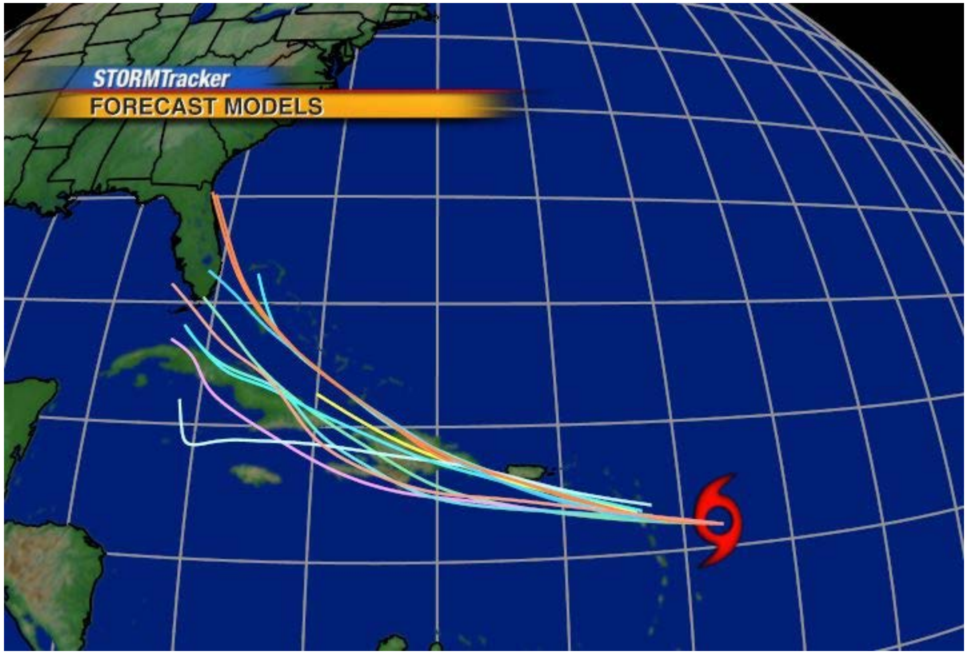
H2: Seismologist don’t know what they are doing (and like to make a fuss so they receive a good share of the funding).

(and yes, we will get to the multi-scale etc. also in this way).

Analogies: Weather forecasting, a respectable science (hurricanes, storms, but I might overdose…)

Challenge 1: Can we reliably forecast the largest earthquakes we will induce **before** we drill?

Analogue 1: Can we reliable forecast the next hurricane to hit Miami in 2016?



Starting point: Know where you are

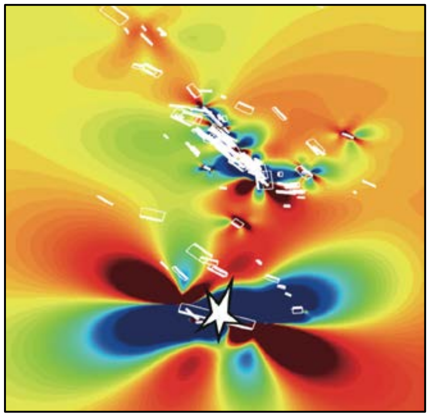
No **hurricanes** in Zurich, but plenty in Florida

→ Known from **empirical evidence**, but there is a good **physical understanding**.

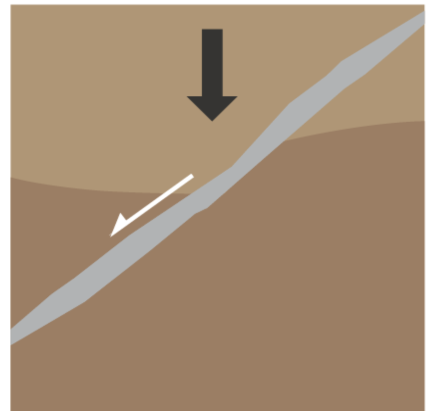
Induced earthquakes: Yes, there are safe places. And we know why. We understand the physics (chemistry/geomechanics) involved reasonably well.

Different physical mechanisms at work

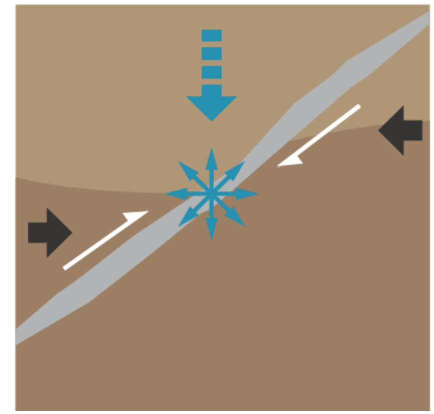
Earthquake interaction



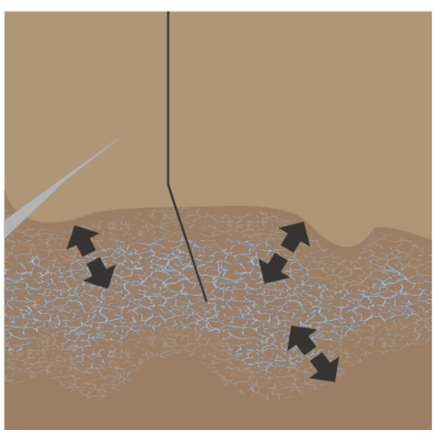
Load change



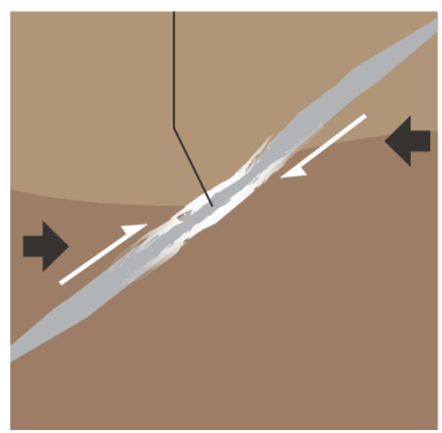
Pore pressure change



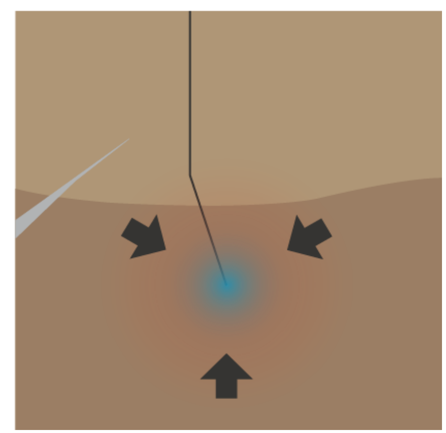
Volume change



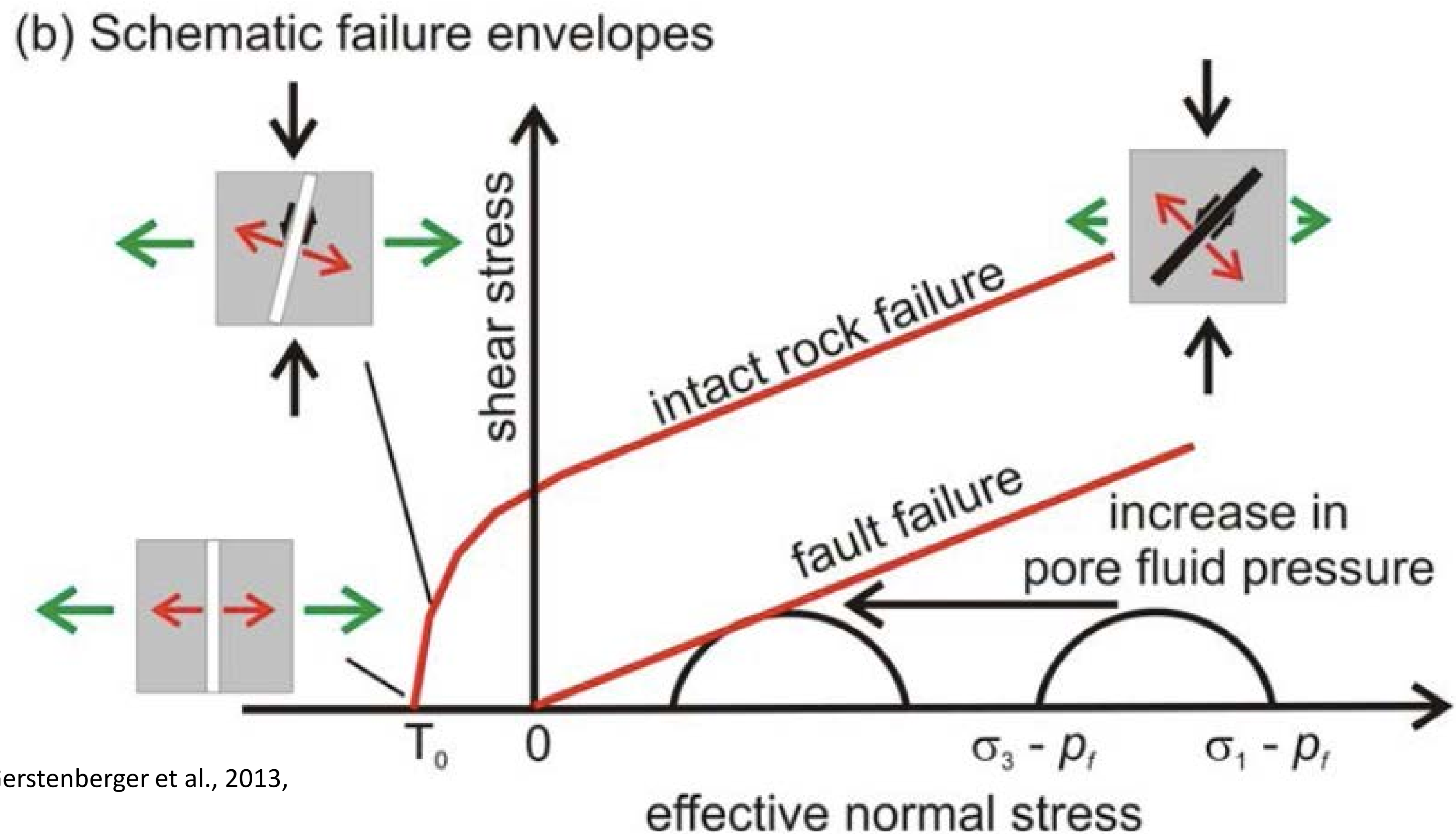
Chemical alterations



Thermal strain



Failure models work generally well



Gerstenberger et al., 2013,

12

Safe places for DGE?

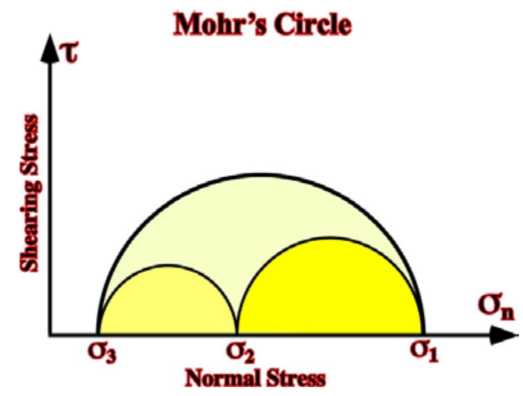
- Places without pre-existing faults
- Places with no differential shear stress accrued through tectonic forces ($\sigma_1 = \sigma_2 = \sigma_3$).

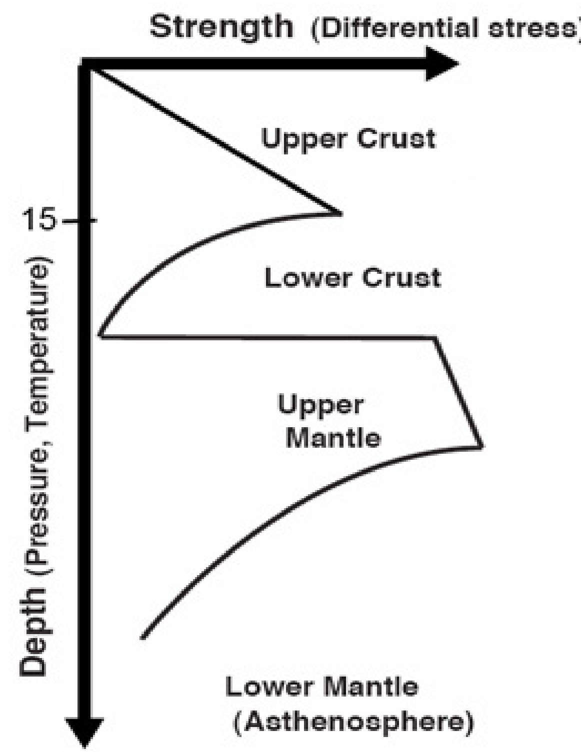
Your best bet: Very shallow, unconsolidated sediments.

Second best: Hot, viscous rocks in volcanic regions.

→ But we want **hot rock in CH**.

→ And the Earth is **critically stressed** in almost all places. So you are in hurricane country, more or less. But we have limited empirical data…

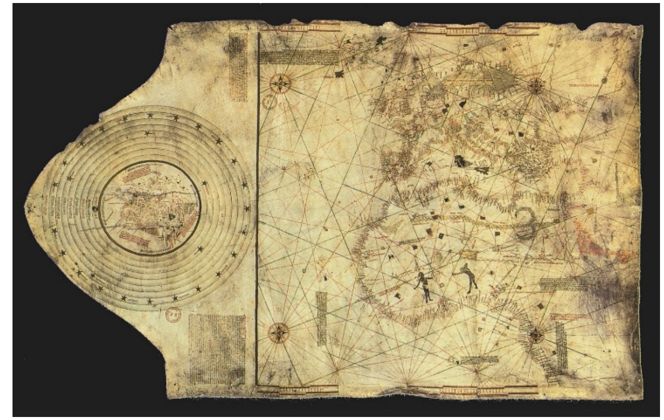


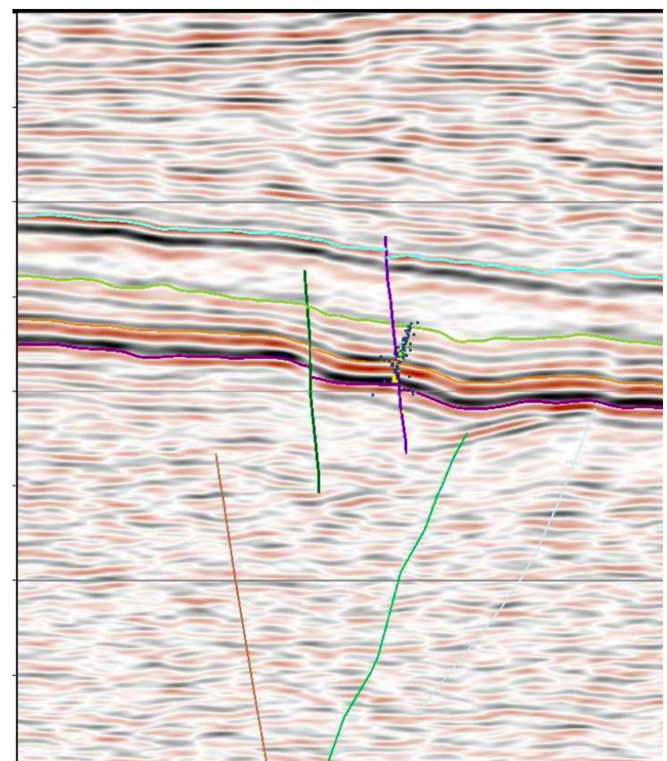


Did Christopher Columbus know how many Hurricanes to expect in Miami?

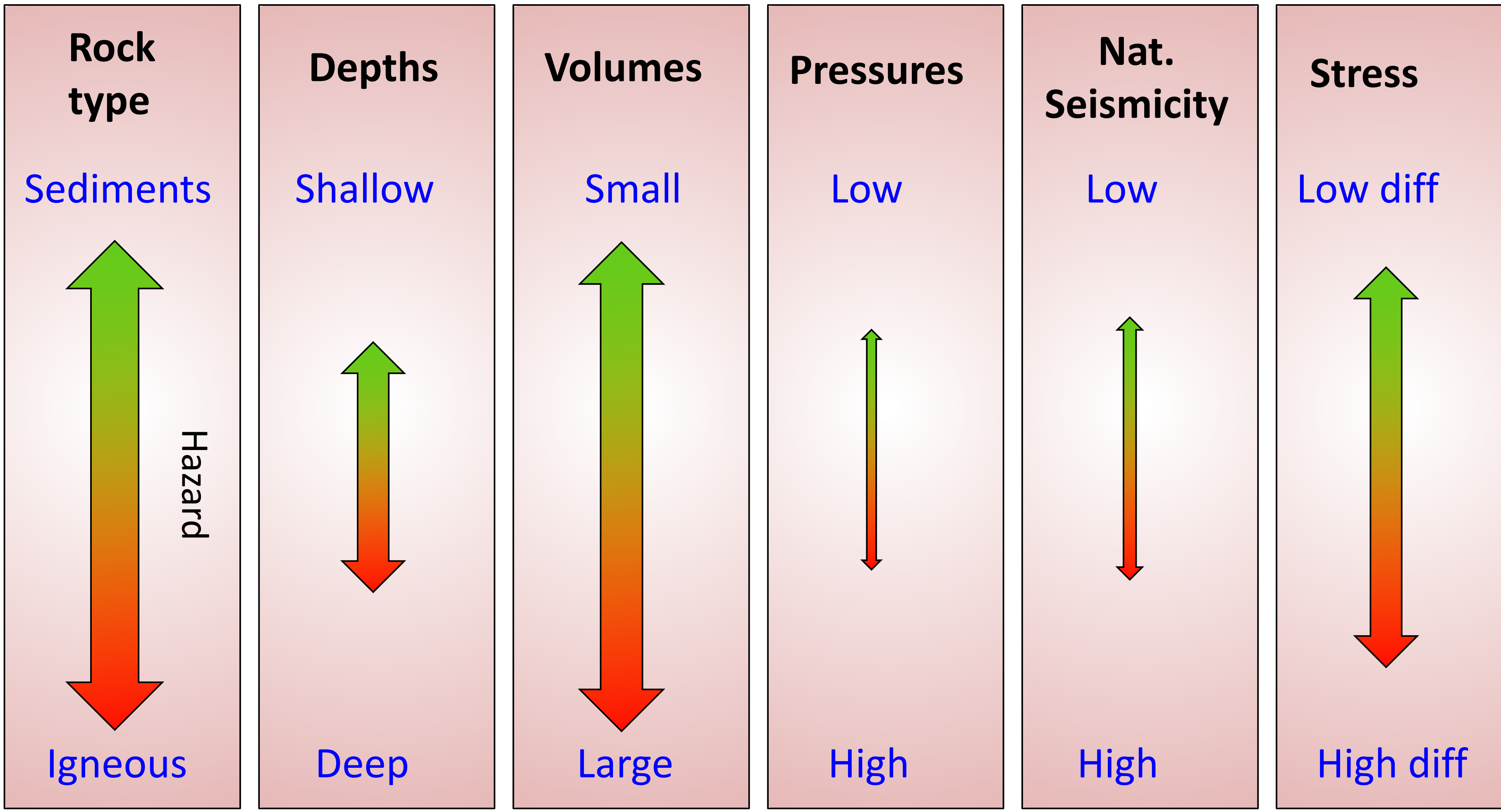
- Not really.
- The world at 5 km depth in the igneous rock below or feet is still, to a certain extent, **Terra Incognita**.
- We have been there in a few places only, and geophysical imaging works poorly in such environments.

→ Expect surprises (also called discoveries).





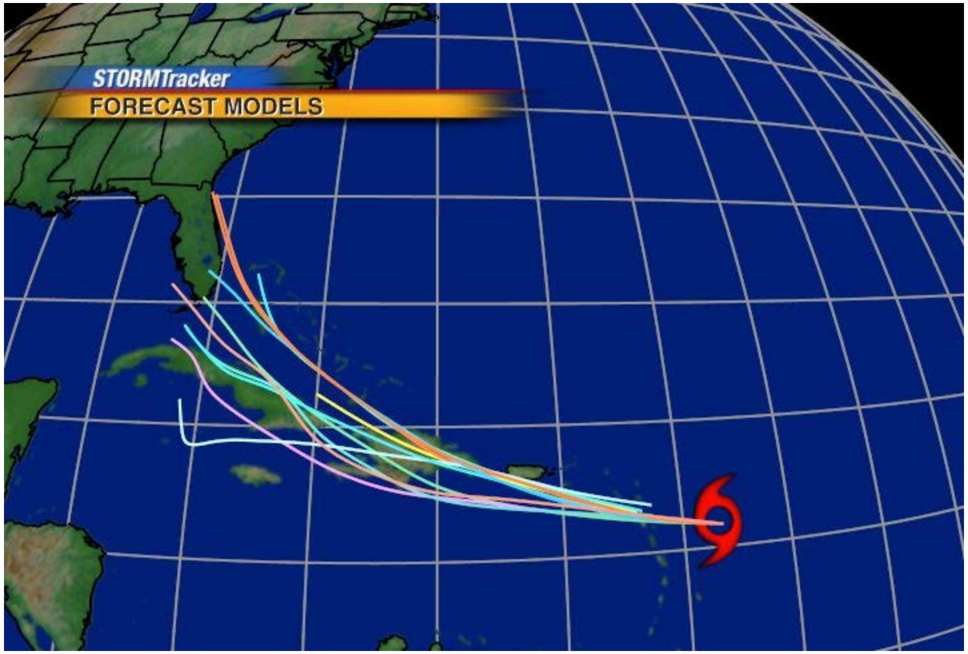
Preliminary list of induced earthquake hazard indicators



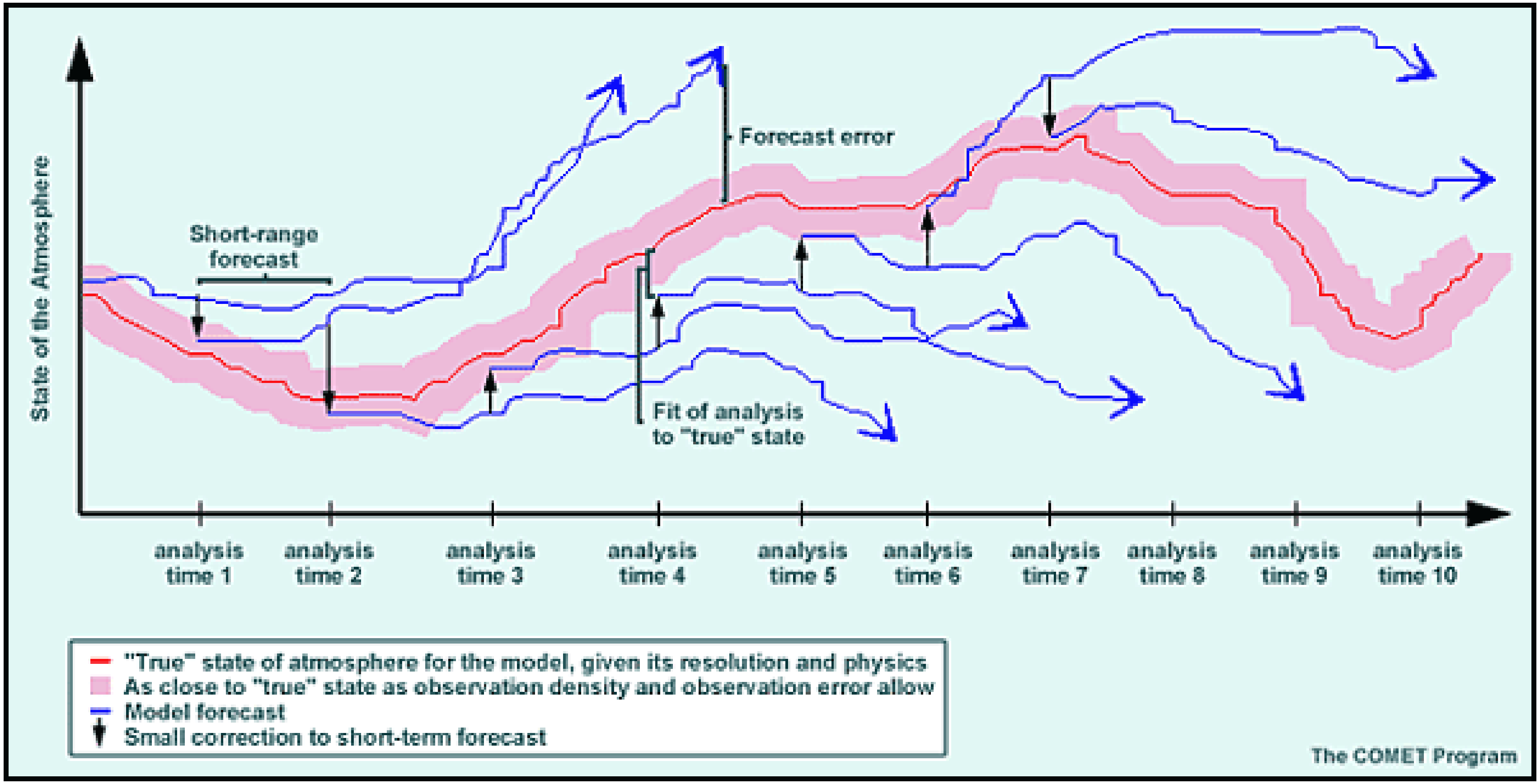
Short term forecasting

Challenge 2: Can we reliably forecast the event that will happen in the next 6 or 24 hours while we create/operate a reservoir?

Analogue 2: Can we reliable forecast the path that a hurricane will take?



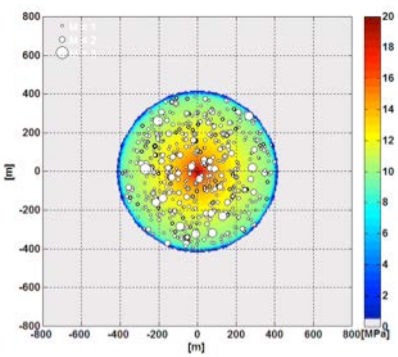
How do meteorologists approach the problem?

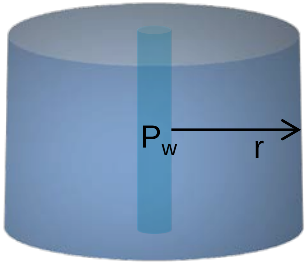


Seismologist have increasingly complex models…

Model Complexity

2012

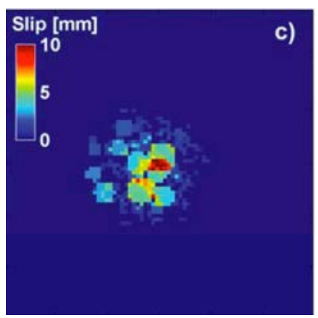


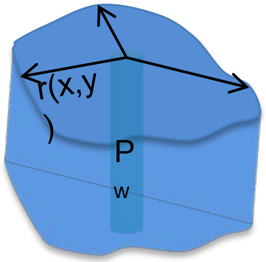


COMSOL

Gischig & Wiemer, 2013
Goertz-Allmann & Wiemer, 2013

2013a

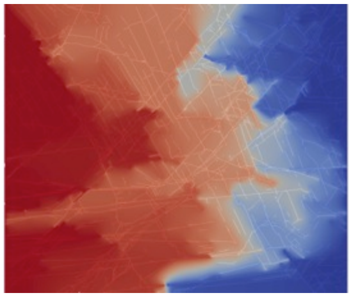


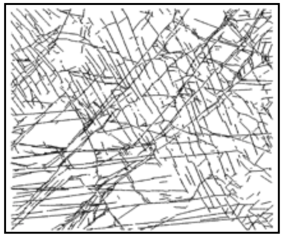


SUTRA

Gischig et al, 2014

2013b

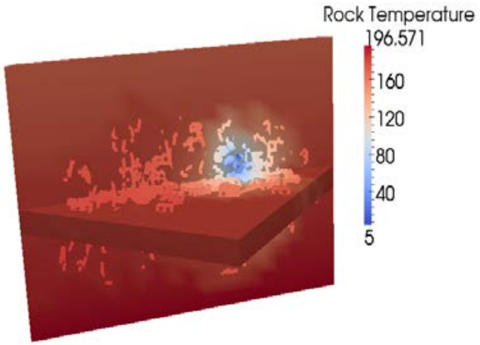




HFR-Sim

Karvounis et al., 2013

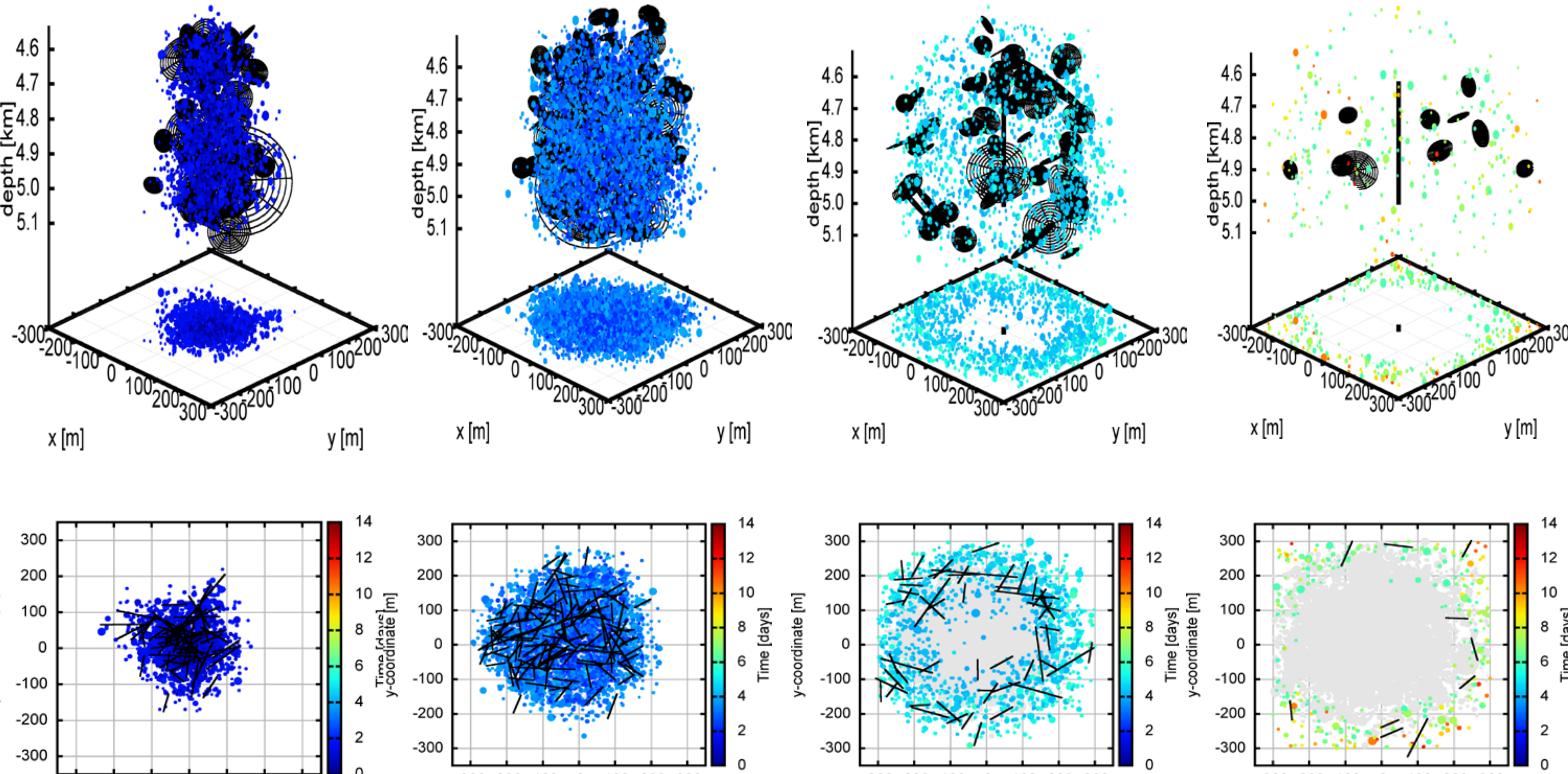
2014a …



HFR-Sim+

Karvounis and Wiemer, 2014

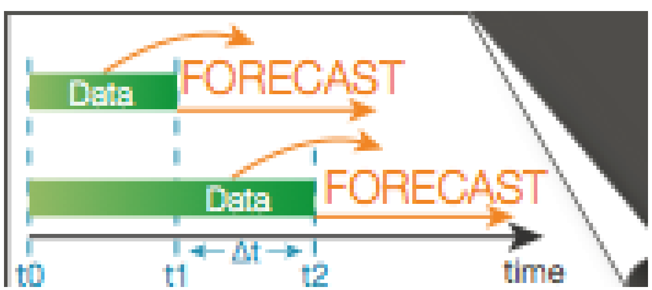
Demonstrative Scenario

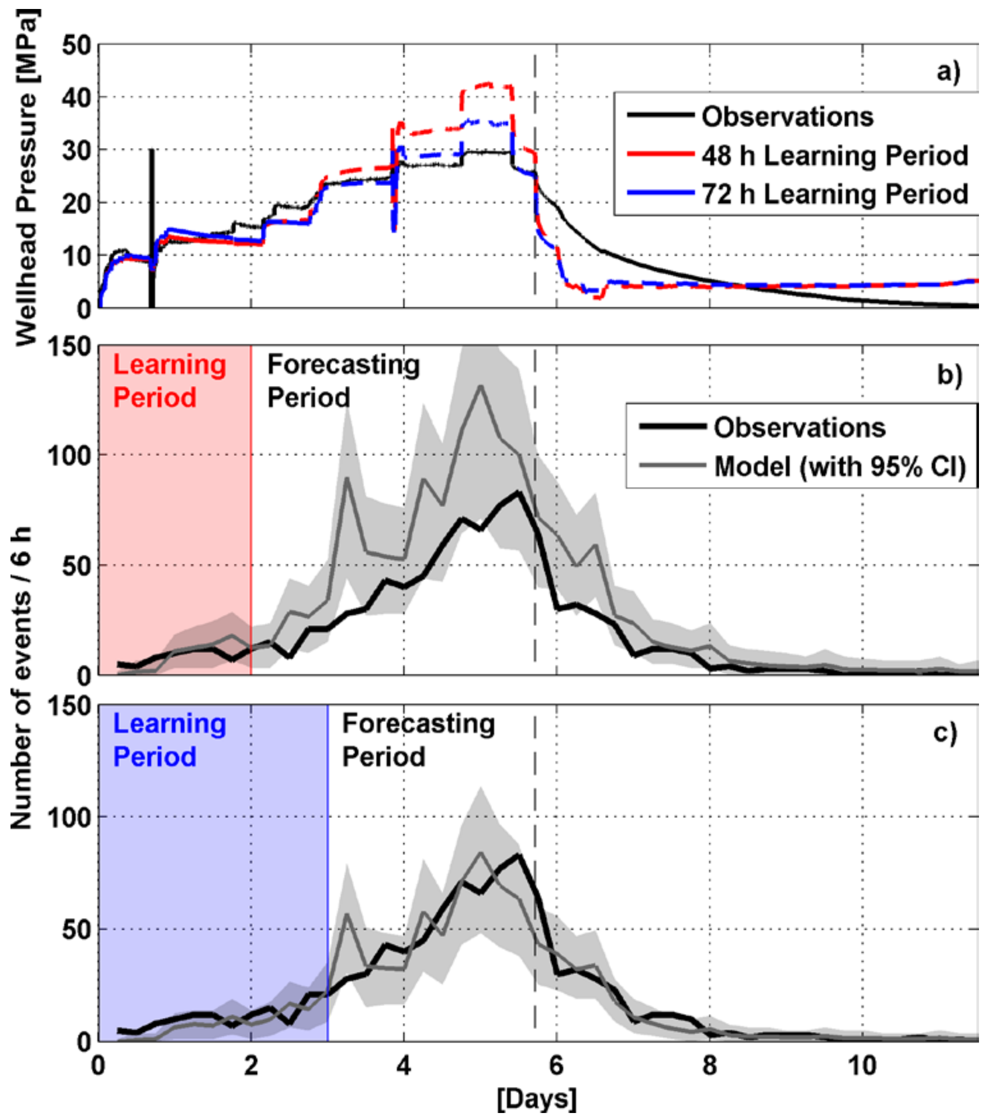


0-2 days *2-4 days* *4-6 days* *6-14 days*

Karvounis et al., 2014

Overall, our Models allow to forecast the average (statistical) behavior of the seismicity while injecting OK….

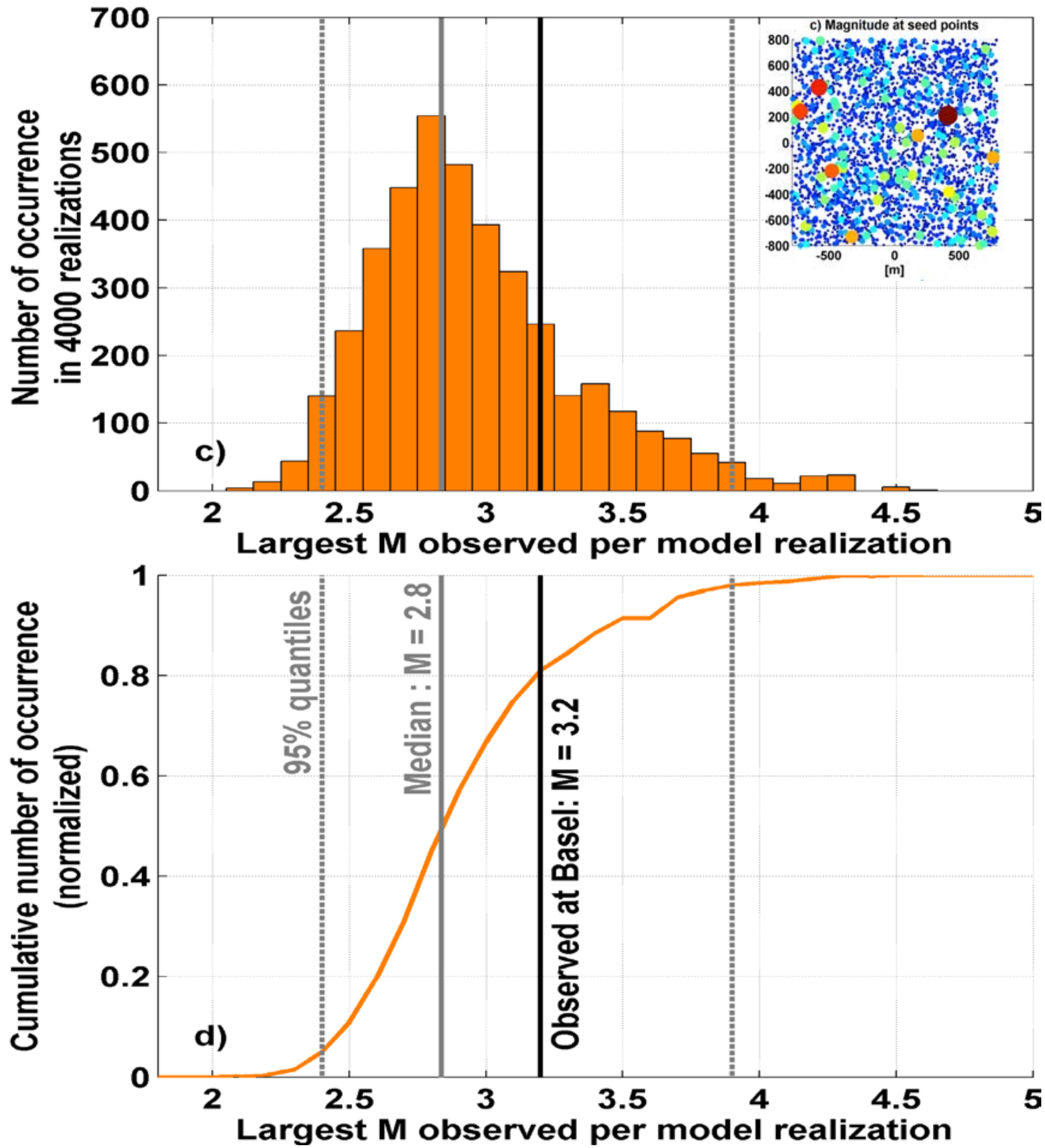




→ Gischig and Wiemer, 2013

But we randomly sample a stochastic event set, and the maximum observed earthquake (the only one that matters) is sampled from the tail:

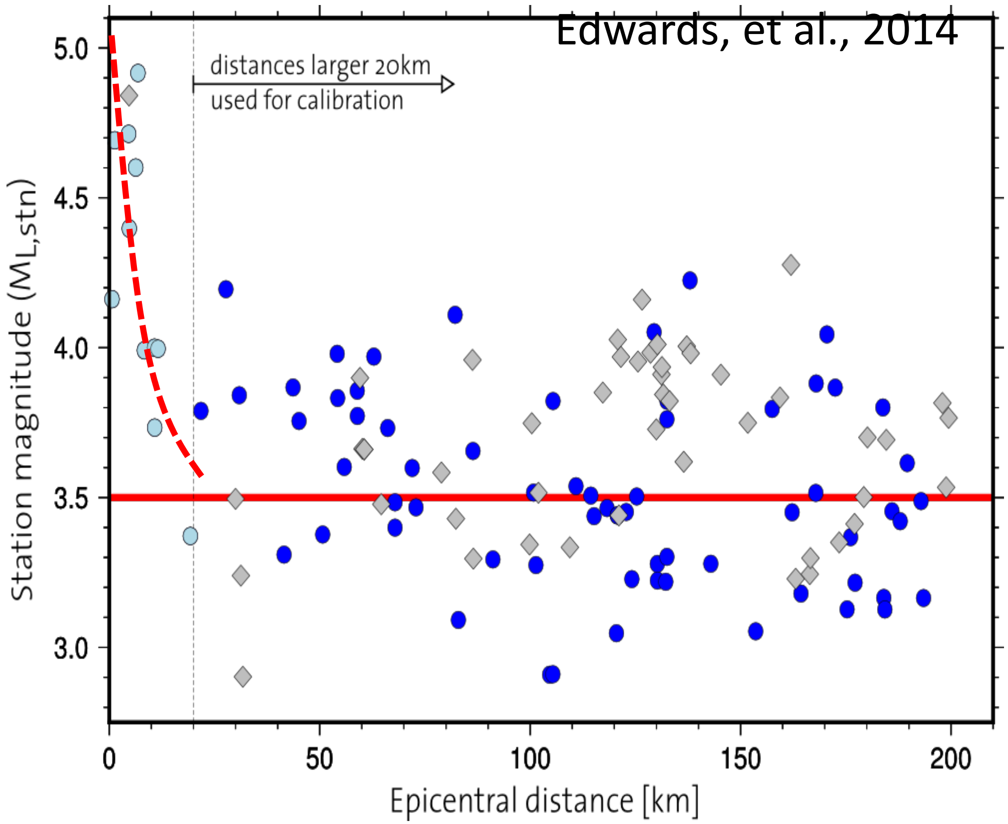
What Basel I could have been just as well…



Predicting what happens with an individual building: Even more tricky

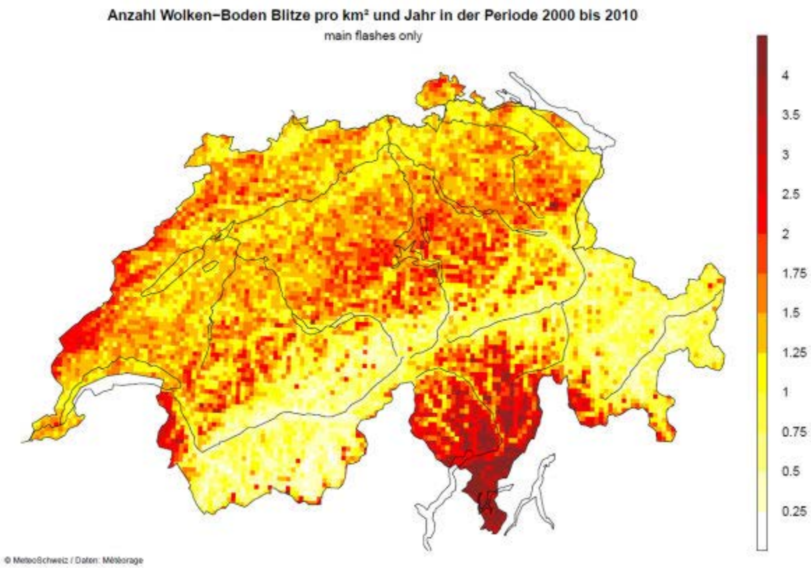
- Model uncertainties and the natural variability in short term forecasting are large.

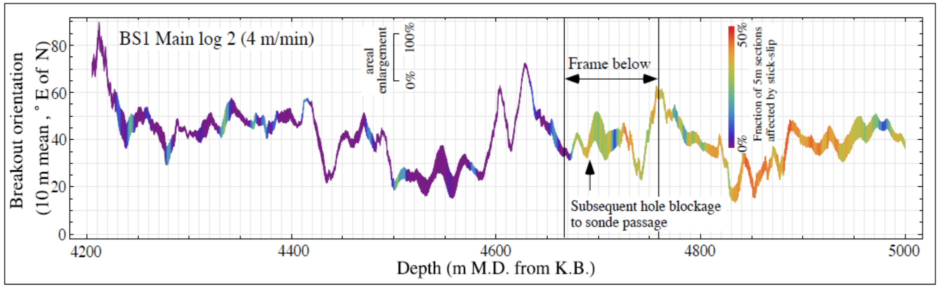
- Even if we like to forecast the ground motion at one place from one earthquake, we have very large uncertainties.



Why is that so?

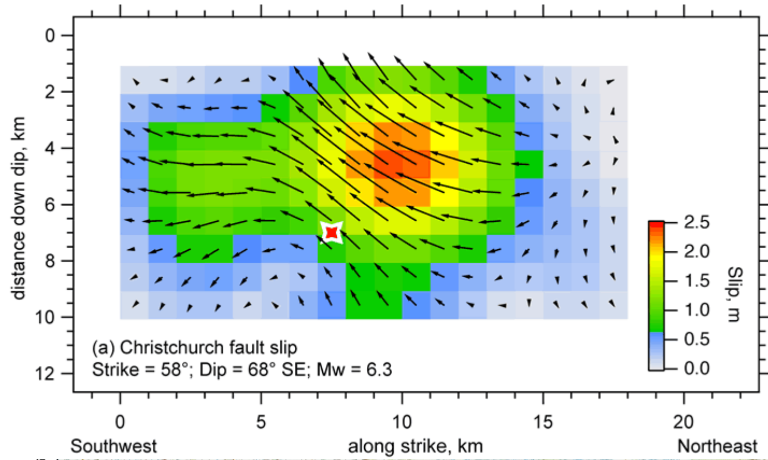
- Because we need to know not only **when** on earthquake will occur, what **size** it will have, but also predict its exact **slip distribution**, know the exact **propagation path** and the **local material properties**, the **local site condition** and the detailed **building vulnerability**.
- All of these are **highly heterogeneous** and unknown at the spatial resolution needed.
- **Analogue:** Predicting how much rain will fall down in a thunderstorm in one specific location.
- Or where lightning will strike, and how strong.

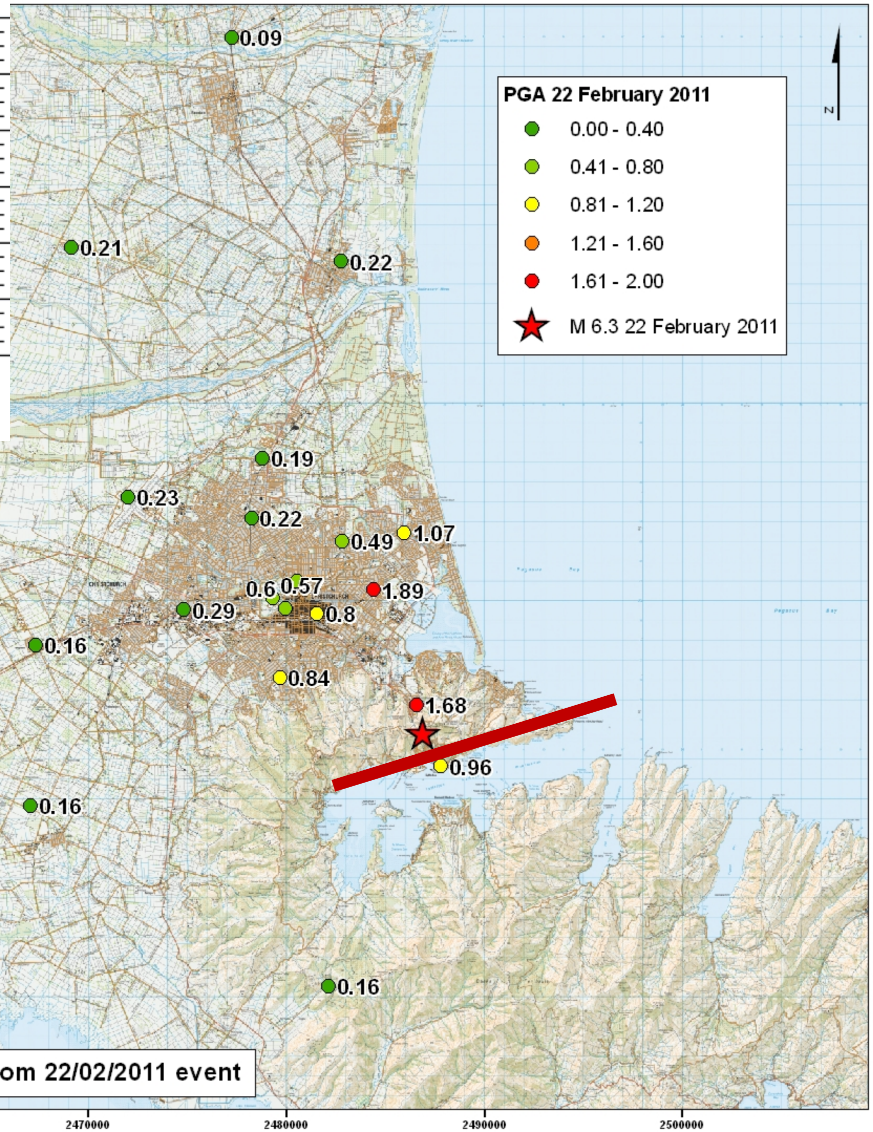




Evans et al., 2012

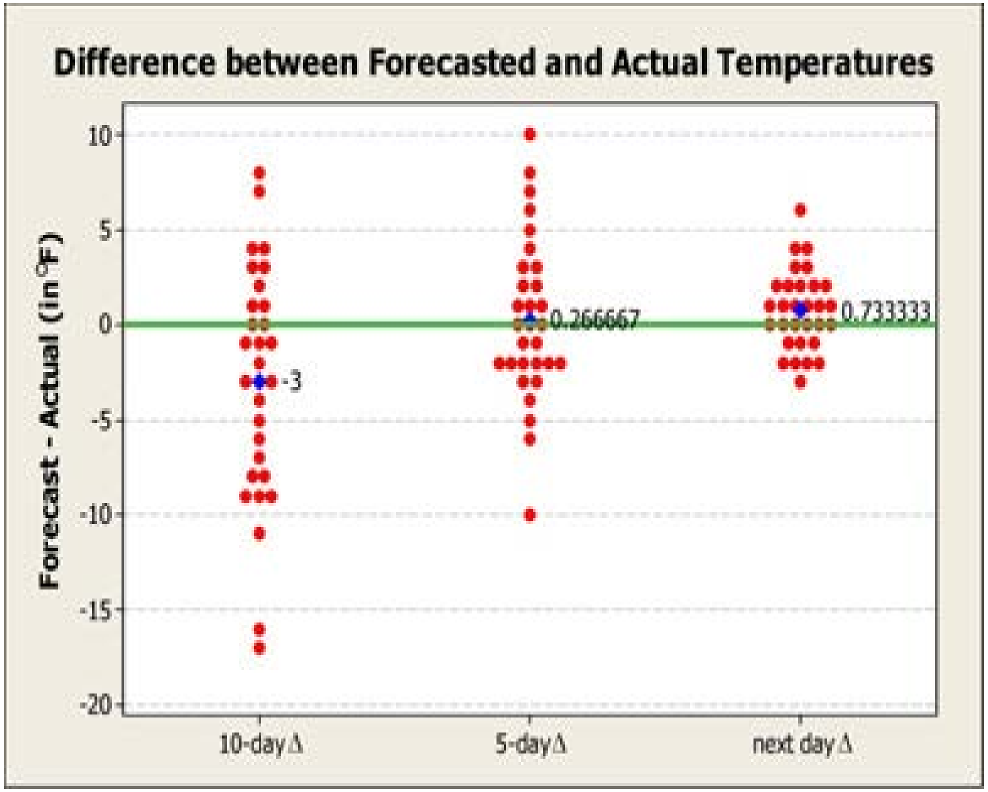
Christchurch: Recorded peak ground motion (PGA)





How do we match up?

- Forecasting the long-term hurricane hazard is possible. On average, we know which areas are more likely to be hit. And why.
- But predicting the next hurricane season in a certain place months, weeks, even days in advance is not possible.
- Why: Because in weather forecasting, the **forecast horizon** is important. Forecasting the next day is relatively easy, forecasting a day in 14 days nearly impossible.



Weather ←→ Earthquakes

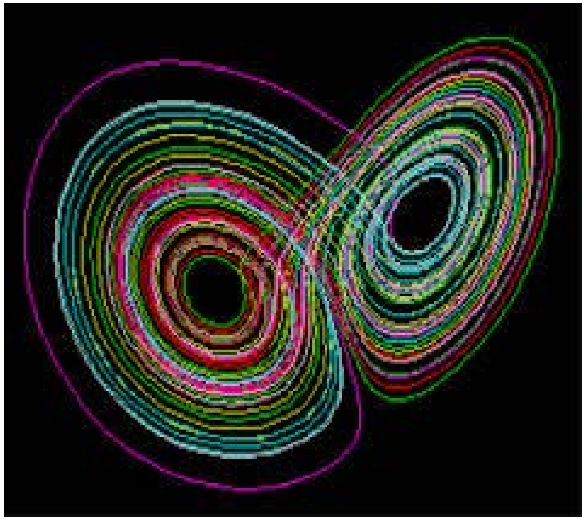
*„**Weather** forecasting is the classic inexact science, relying on the complex mutual interactions of **wind, currents, precipitation, tides, humidity and temperature** variations, and a million other variables (...) . To say forecasting the weather is tricky is putting it mildly indeed.“*

*„**Earthquake** forecasting is the classic inexact science, relying on the complex mutual interactions of **stress, fluids, tides, faults and temperature variations**, and a million other variables across the Earth Crust. To say forecasting eartqhuakes is tricky is putting it mildly indeed.“*

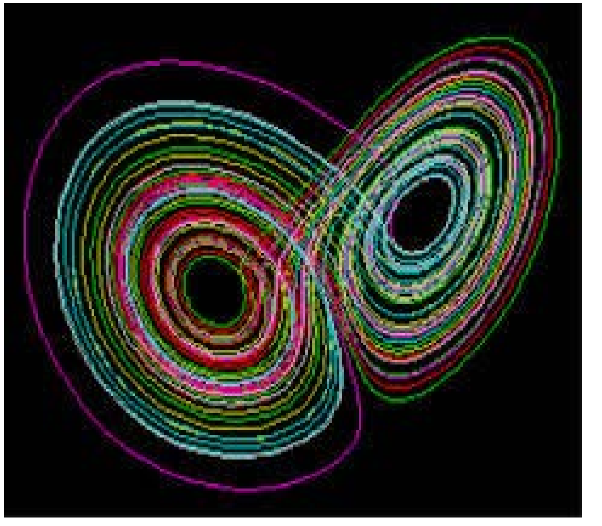
Chaos

“In fact, it was while working on weather prediction that mathematician Edward Lorenz began to conceive **Chaos Theory**, the mathematical theory which says some systems, **highly sensitive to initial conditions**, are simply too complex to be predictable over the long term.

Weather **(“and Earthquakes!”**) is the poster child for chaos theory .



Chaos



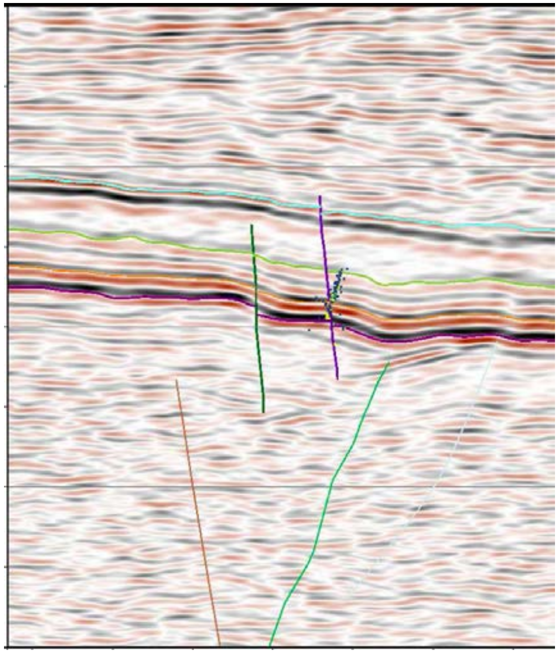
Chaos theory studies the behavior of dynamical systems that are highly sensitive to initial conditions.

Small differences in initial conditions yield widely diverging outcomes for such dynamical systems, **rendering long-term prediction impossible in general**.

This happens even though these systems are deterministic, meaning that their future behavior is fully determined by their initial conditions, with no random elements involved

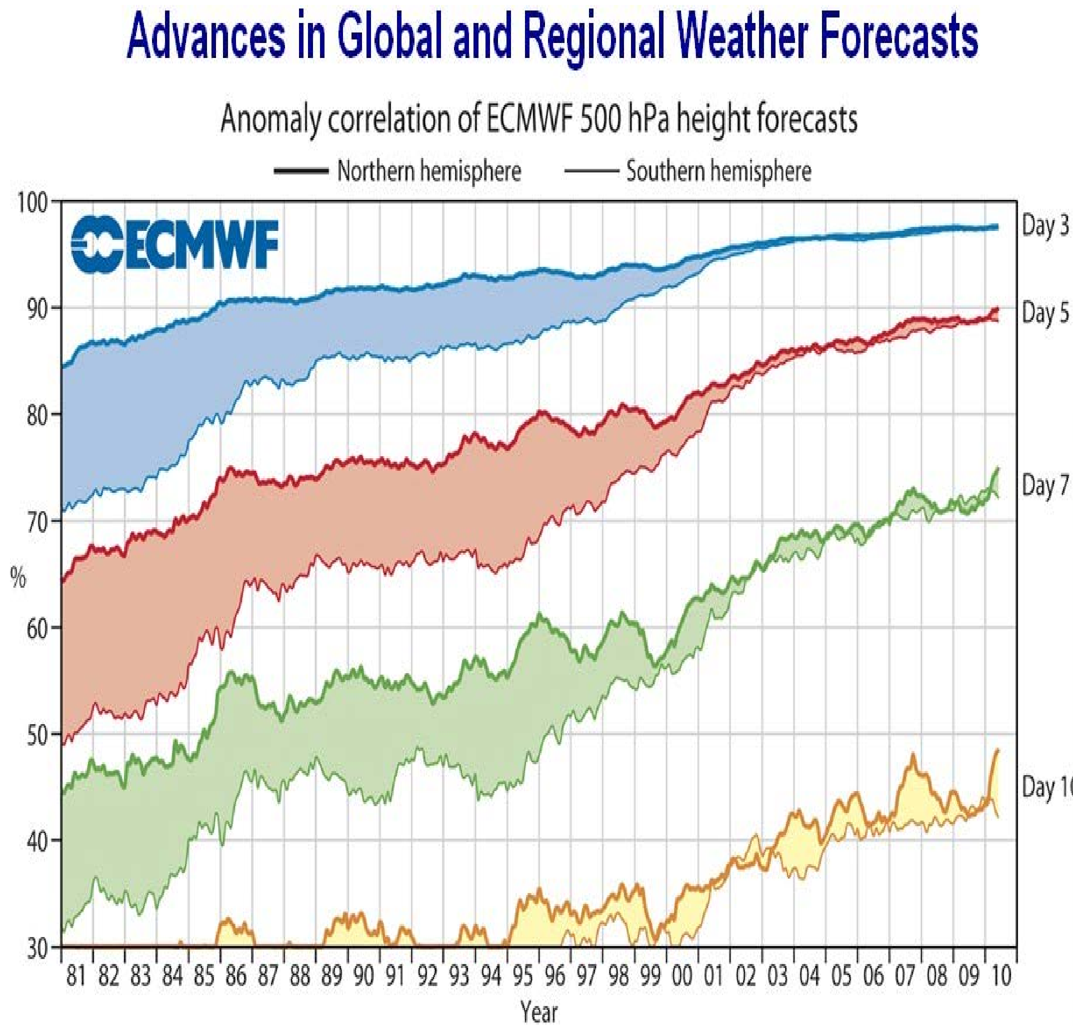
Are we faced with a chaotic system?

- Not necessarily (although earthquakes overall, and so far, cannot be predicted).
- But we are know so little about the initial conditions, how can we expect to make deterministic forecasts even if it would be possible in principle?
- The sky is transparent, the Earth is not. We cannot measure nor image stresses on faults, we can hardly image the location of major faults themselves.
- You can see a storm coming days before, we may not know that there is a major fault, ready to go, just a few tens of meters from our injection.



But does that stop weather forecasting?

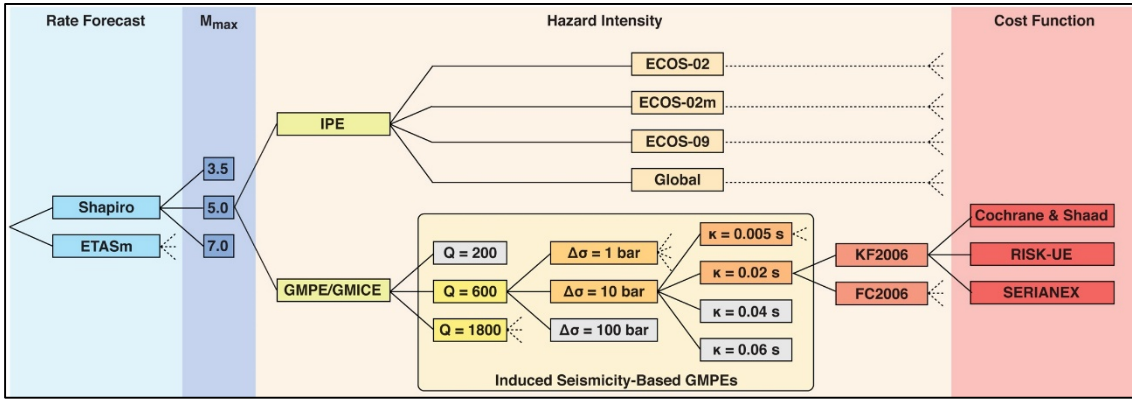
- *"Between 1981 and 2010, the accuracy of 3-day weather forecasts in the northern hemisphere rose from about 70 percent to about 98 percent"*
- Steady evolution, hard, dedicated work and improvements in models, as well as data were needed.
- This I think is the path for induced earthquake research also.



Accept the inevitable: Some things are difficult. No quick fixes. No silver bullet. Sorry.

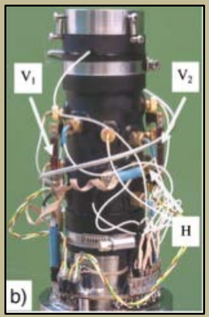
- **But no need to give up.**
- Accept the uncertainty and the lack of long-term predictive power, we do so all the time.
- Do not be afraid of regulators, and the public, they can accept uncertainties also. But risks need to be quantified and insured against.
- Risk and **perceived benefits** must be balanced.
- **Transparency** is essential.
- Mitigation help (Traffic lights). Keep also natural seismicity in mind
- **And:** There is a lot of work to do, to improve our models, to calibrate and validate/test them, to generalize them etc.

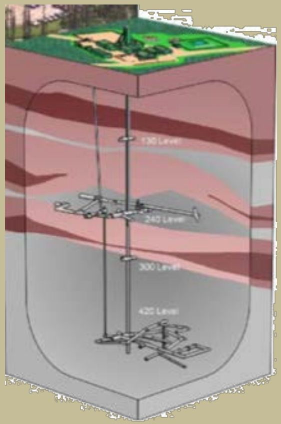
→ **Enter SCCER**

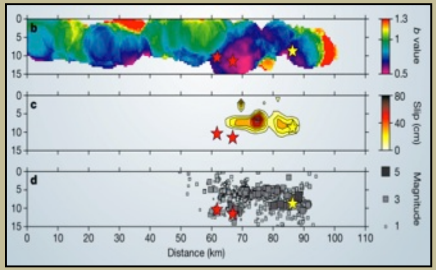


Multi-scale, integrated and cross-disciplinary R&D is needed

10 cm | 10 m | 100 m | 1 km | 10 km



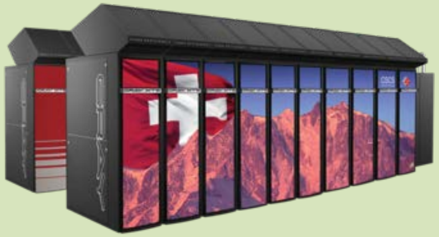


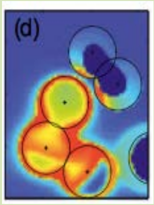


Laboratory Scale

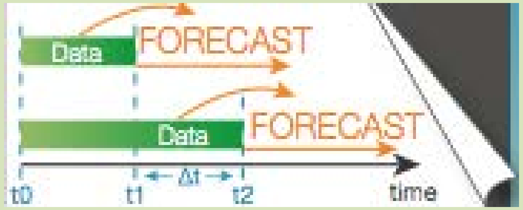
Underground Lab Scale

Natural Systems

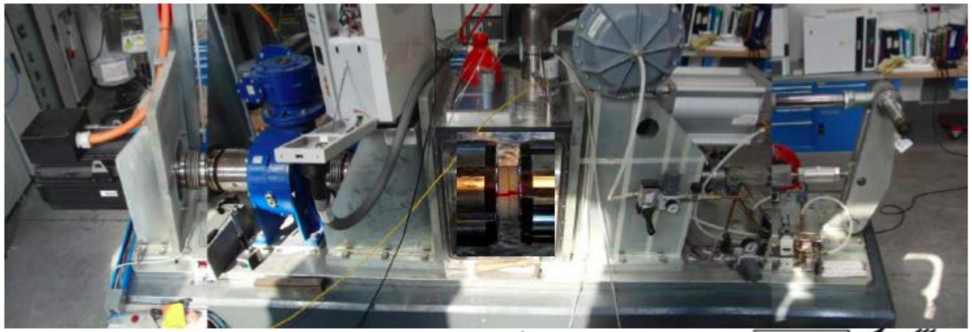


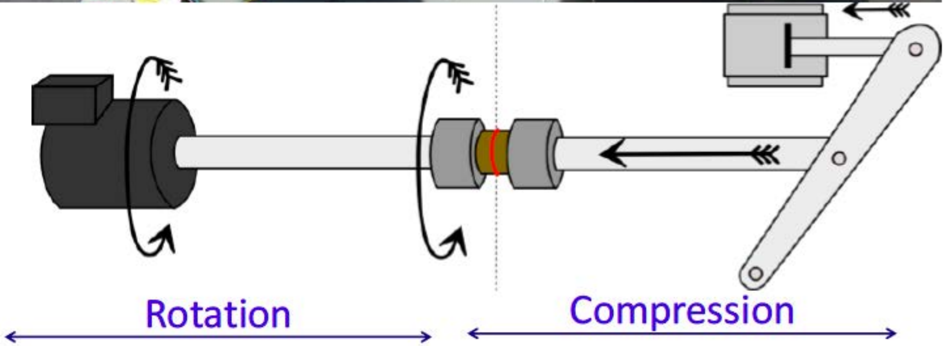


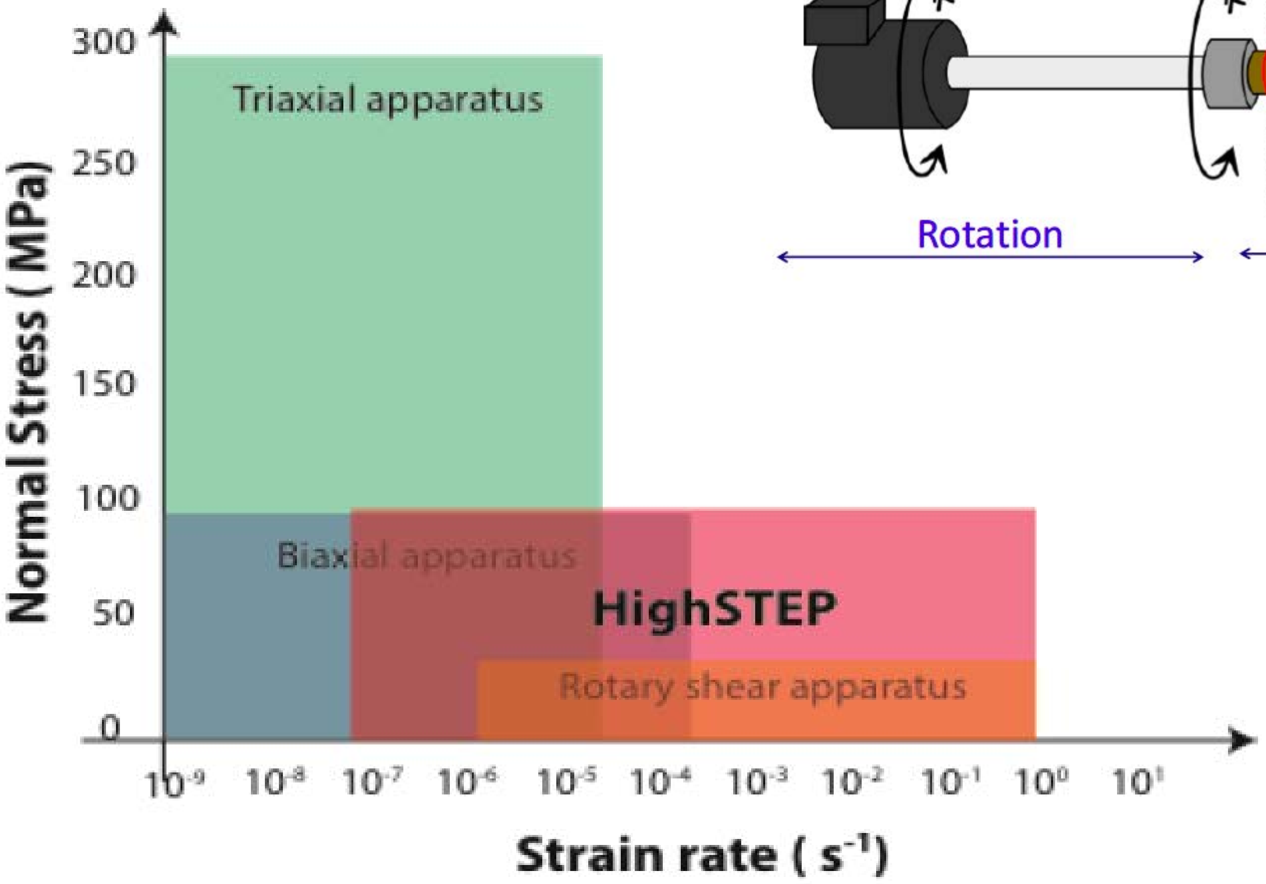
High Performance Computing, Modeling & Validation



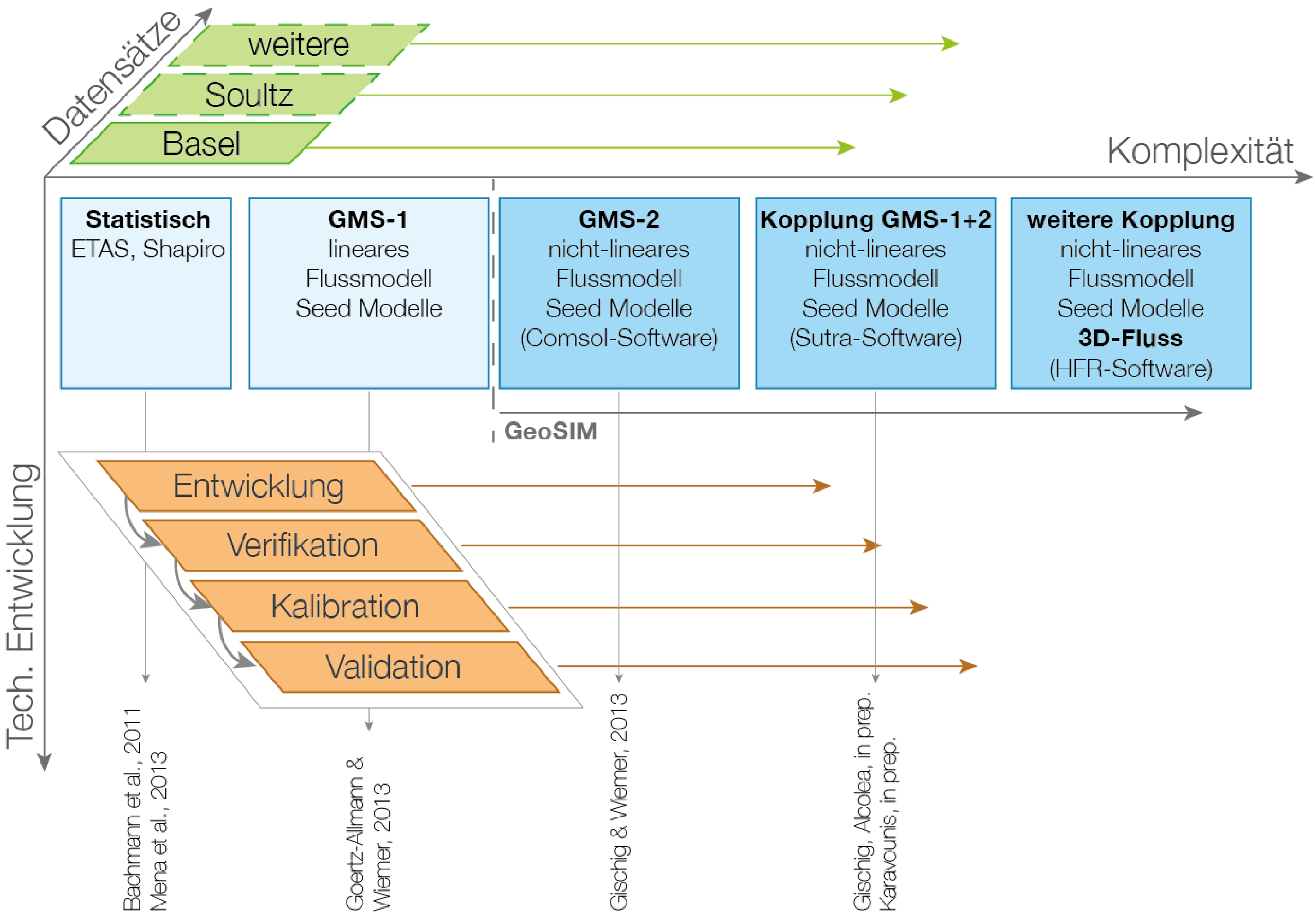
HIGHSTEPS



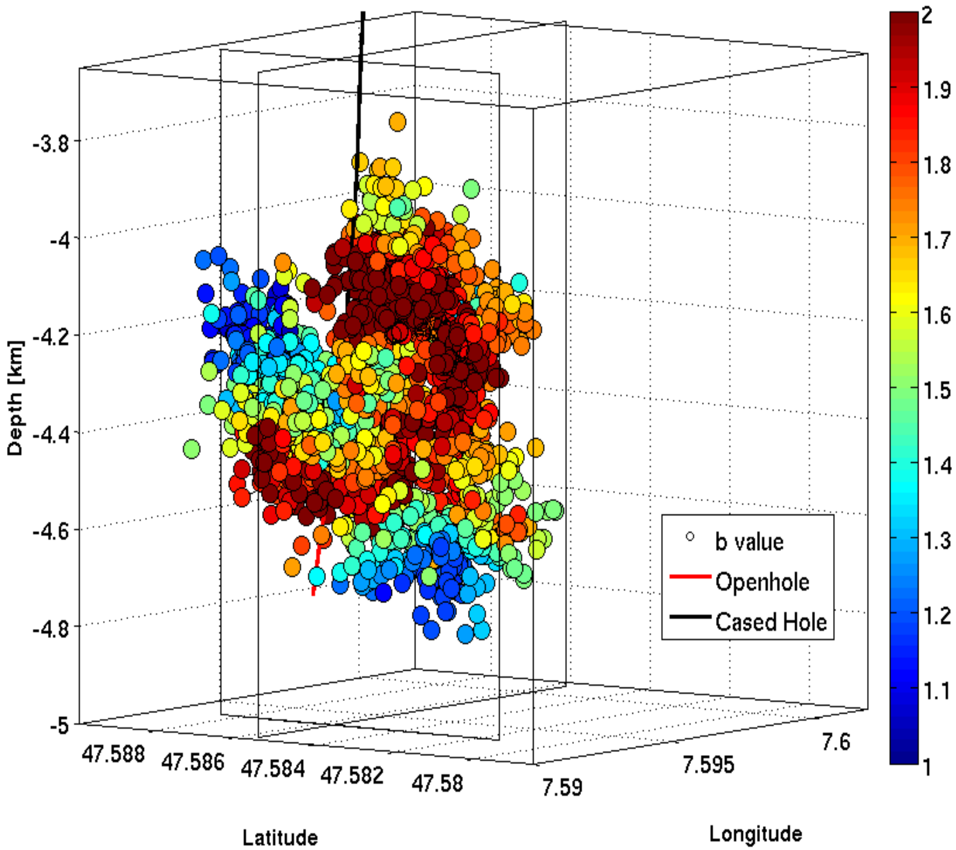

Rotation
Compression


Normal Stress (MPa)
300
250
200
150
100
50
0
Triaxial apparatus
Biaxial apparatus
HighSTEP
Rotary shear apparatus
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
Strain rate (s^{-1})

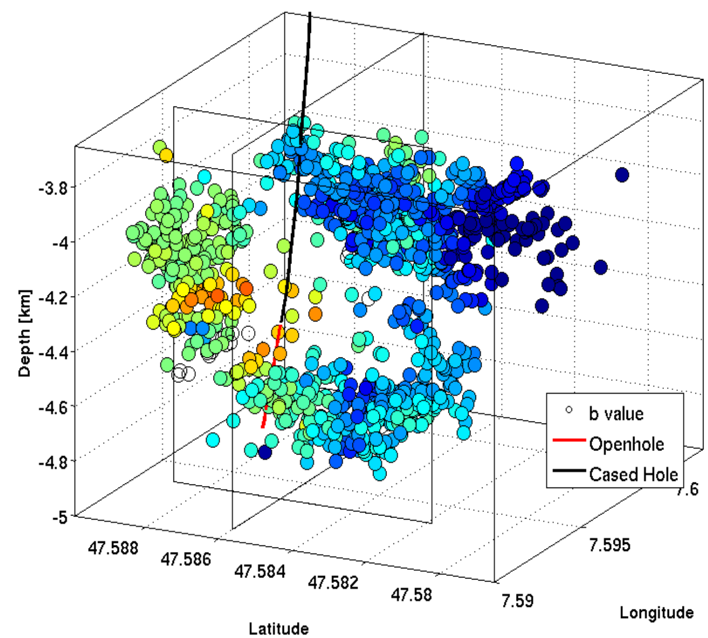
A testbench for validation



Testable hypothesis: b-value as a function of pore pressure: Basel – and soon in the lab



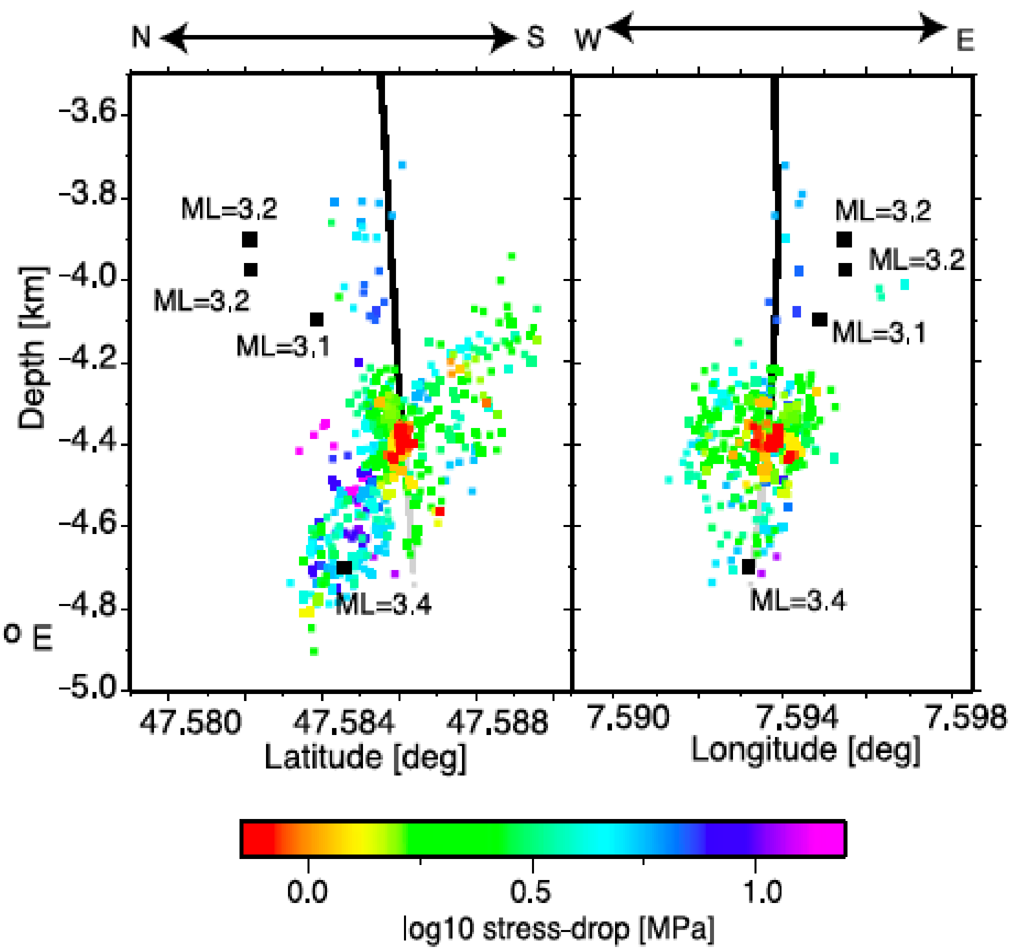
During injection

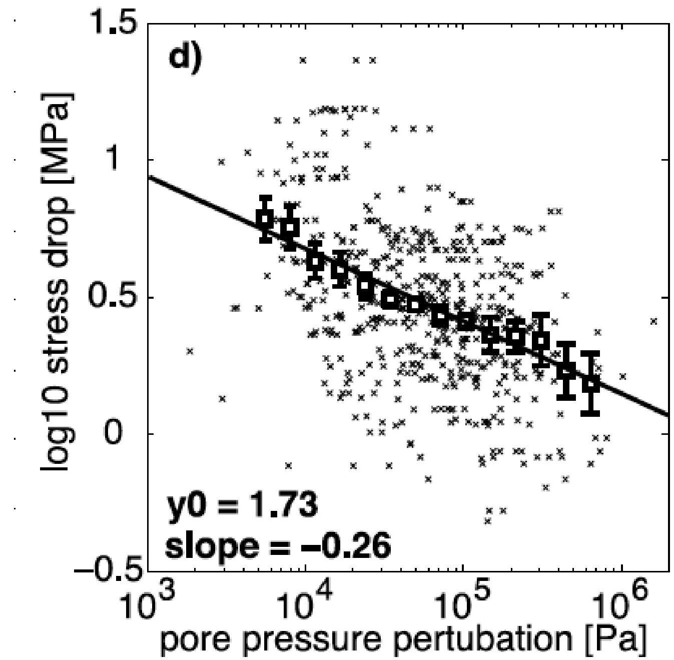


After injection

➔ *Bachmann et al. 2012*

Linking stress-drop of micro-earthquakes and pore pressure in Basel – and soon in the lab

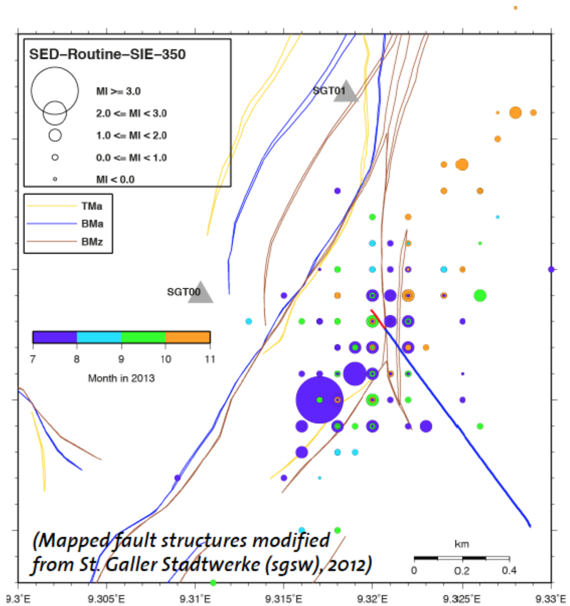




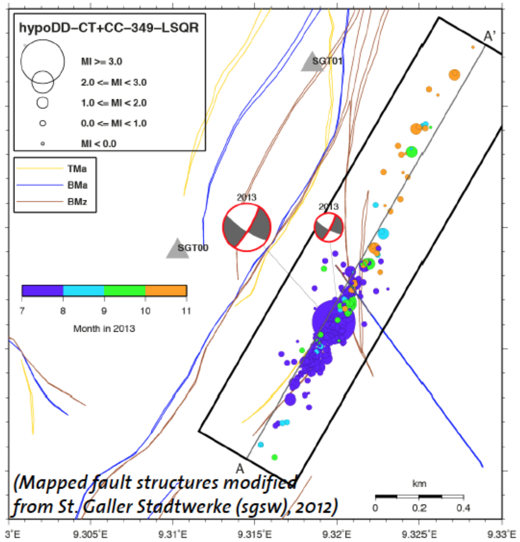
→ Goertz-Allmann et al, 2011, 2013

Earthquake relocation is key for process understanding – at any scale.

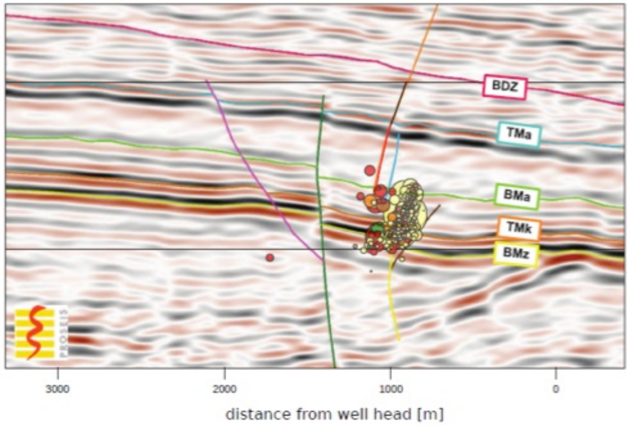
Linking process and structure in St. Gallen



SED Routine Locations:
- Manual Picks (P+S)
- Grid-based location (NonLinLoc)
- 3D P-wave velocity model (+ const. Vp/Vs)



Double-Difference Relocations:
- Differential times from manual picks (P+S)
- Differential times from cross-correlation (P+S)
- hypoDD
- Initial locations from VELEST locations
- Minimum 1D P+S model



→ Diehl et al., 2014

Induced Seismicity: A Cross-Disciplinary Challenge!

Structural Engineering

Statistical Seismology

Geological Modeling

Earthquake Physics

Hazard, Risk Assessment

Fluid Dynamics

Exploration Geophysics

Numerical Modeling

Rock Physics

Social Science

SCCER SoE

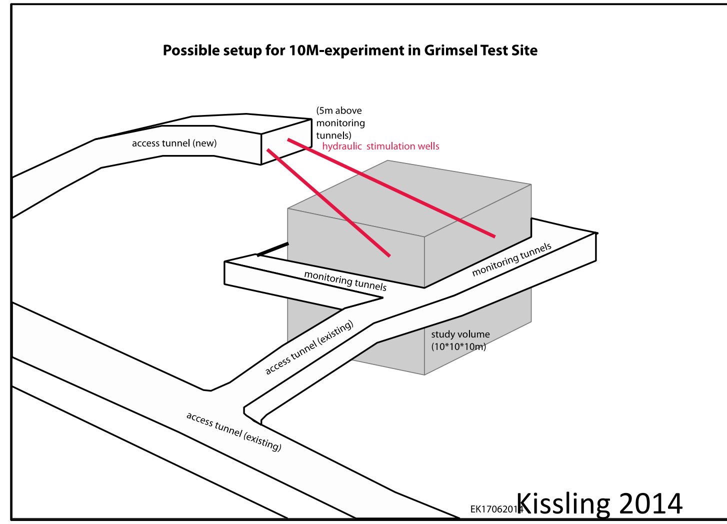
Swiss Roadmap for understanding induced seismicity

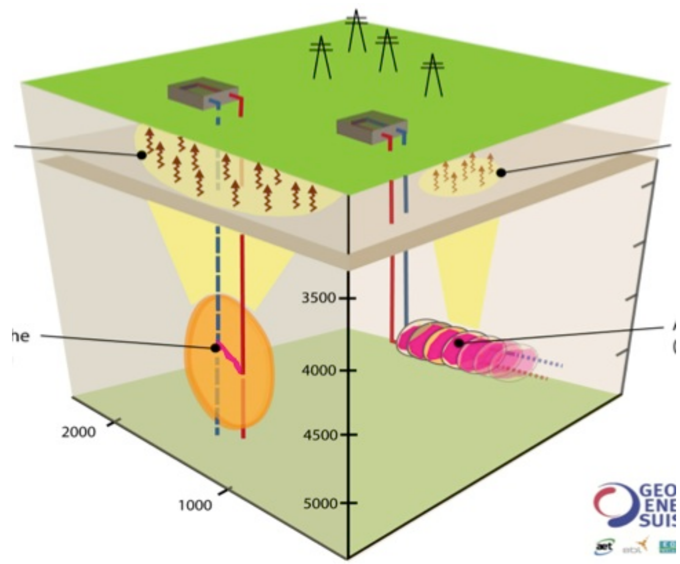
- Bring together key competence in numerical modeling, exploration and risk governance.
- **Rock physics lab Phase 1**: HIGHSTEPS
- **Underground Lab Phase 1 -** Scale 1:100 at Grimsel: start 2015:
- **Underground Lab Phase 2 -** Scale 1:10. Site TBD: start 2016.
- **EGS Pilot and Demonstration project** in 4-5 km depth with industry partners: From 2016.

→ Integration with various Horizon2020 calls ongoing.

→ Industry opportunities: Managing IS is a global challenge!

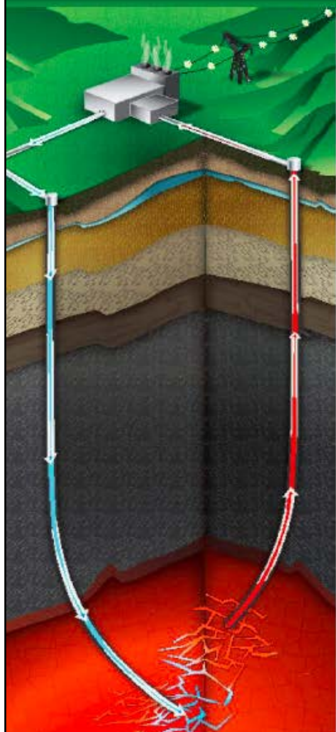
→ Global collaboration: A joint IPGT project is on the horizon.





US Approach: FORGE

Frontier Observatory for Research in Geothermal Energy (FORGE)



- High-risk / high-reward
  - Drilling technology, well construction and integrity
  - Advanced characterization tools and methods
  - Stimulation technologies
- Highly-integrated technology testing
- Live data site
- Explicit partnerships with the research community and other subsurface stakeholders
- Methodology for reproducing large-scale, economically-sustainable heat exchangers

Site Selection & Planning → Site Preparation & Characterization → Technology Testing & Evaluation → Closeout

6 - 7 Years

Source: Doug Hollet, DOE

Thank you

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Swiss Seismological Service

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Program & Contributions

Conference Venue & Travel Information

Registration, Abstract Submission & Deadlines

Sponsors

AGIS Workshop on Induced Seismicity

Welcome to the AGIS Workshop on Induced Seismicity from 10. - 13. March, 2015, in Davos Schatzalp, Switzerland.

Understanding and managing induced and triggered seismicity is a key challenge for many georesource applications. Recent incidents, changes in the risk perception of societies and regulators, but also new kinds of applications require advancing the scientific understanding of induced seismicity as well as validated frameworks for risk governance.

This scientific workshop summarizes the state of the art from around the globe and across different industrial applications. We also strive to establish current best practice and develop a roadmap for future research needs.

Topics

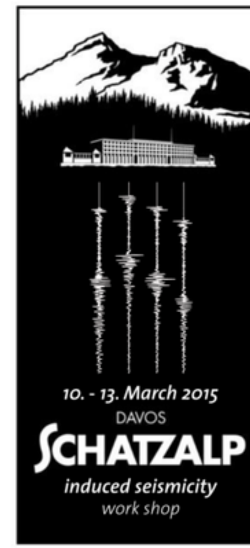
- **Extraction induced Seismicity**
- **Injection Induced Seismicity**
- **Modeling of Induced Seismicity**
- **Scaled Experiments**
- **Monitoring and Analysis of Induced Seismicity**
- **Industry Projects & Perspective**
- **Risk Governance, Societal Acceptance & License to Operate**
- **Pilot and Demonstration Sites & Future Initiatives**

Venue

The workshop takes place at the Swiss Historic Hotel Schatzalp, which is located within the Swiss mountains, at an altitude of 1861 m, and 300 m above the city of Davos.

The nostalgic Art Nouveau style building with its Belle Epoque atmosphere was already described in Thomas Mann's novel "Zauberberg", and 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.

Induced Seismicity Workshop, 10. - 13. March 2015, Davos



Download the first circular here.

www.seismo.ethz.ch/schatzalp/