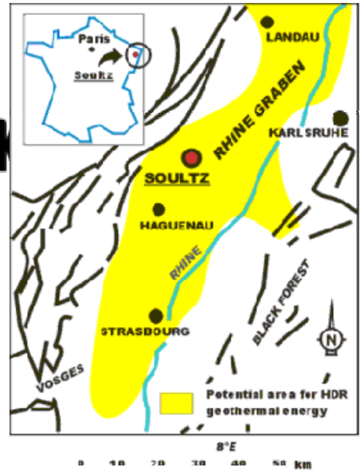
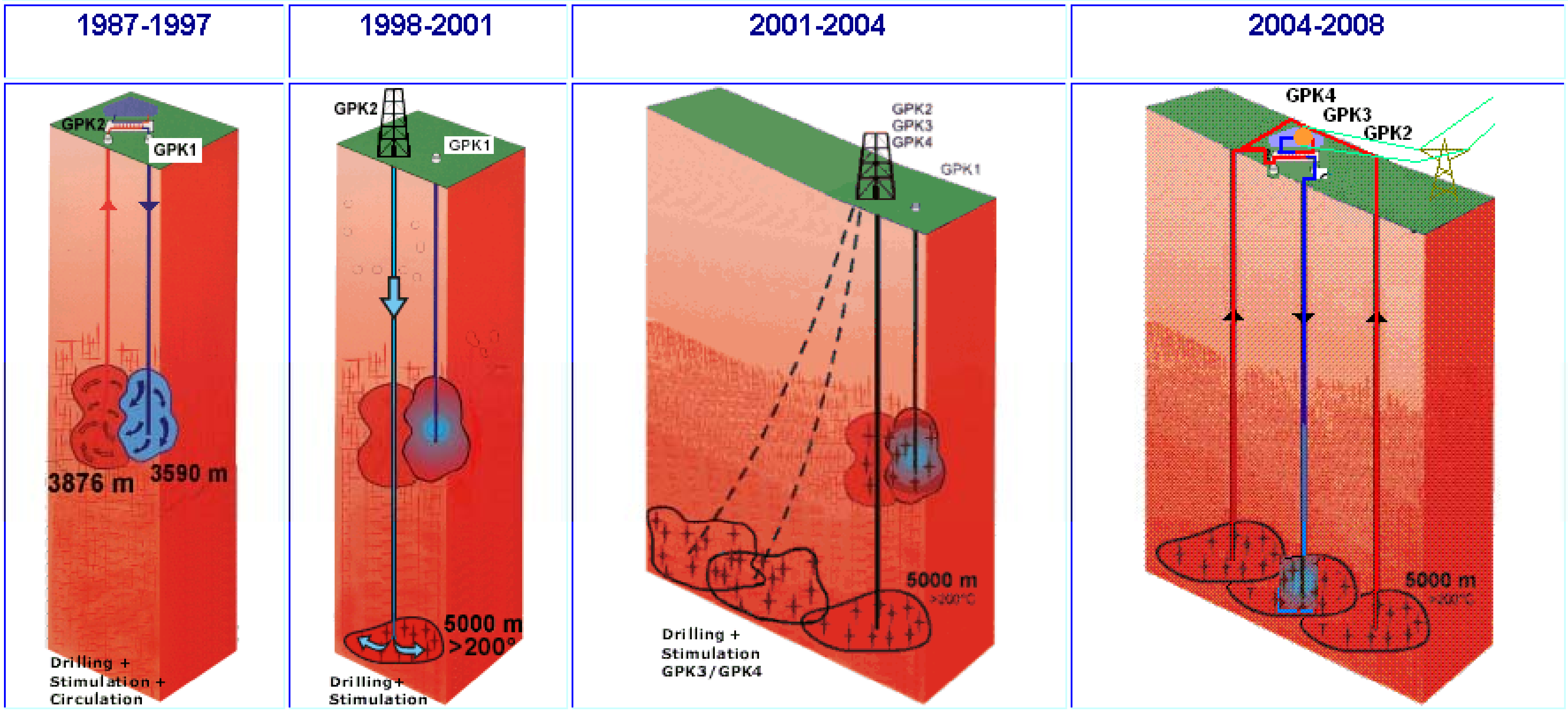
content

- Solicited events
- Best practices before Basel
- Unsolicited events
- GEISER
- Future directions

Enhanced Geothermal Systems

- EU research project > 20 years
- 3 wells > 5 Km deep
- Comprehensive Fracturing programe
- 3MW$_{el}$ Power via ORC plant





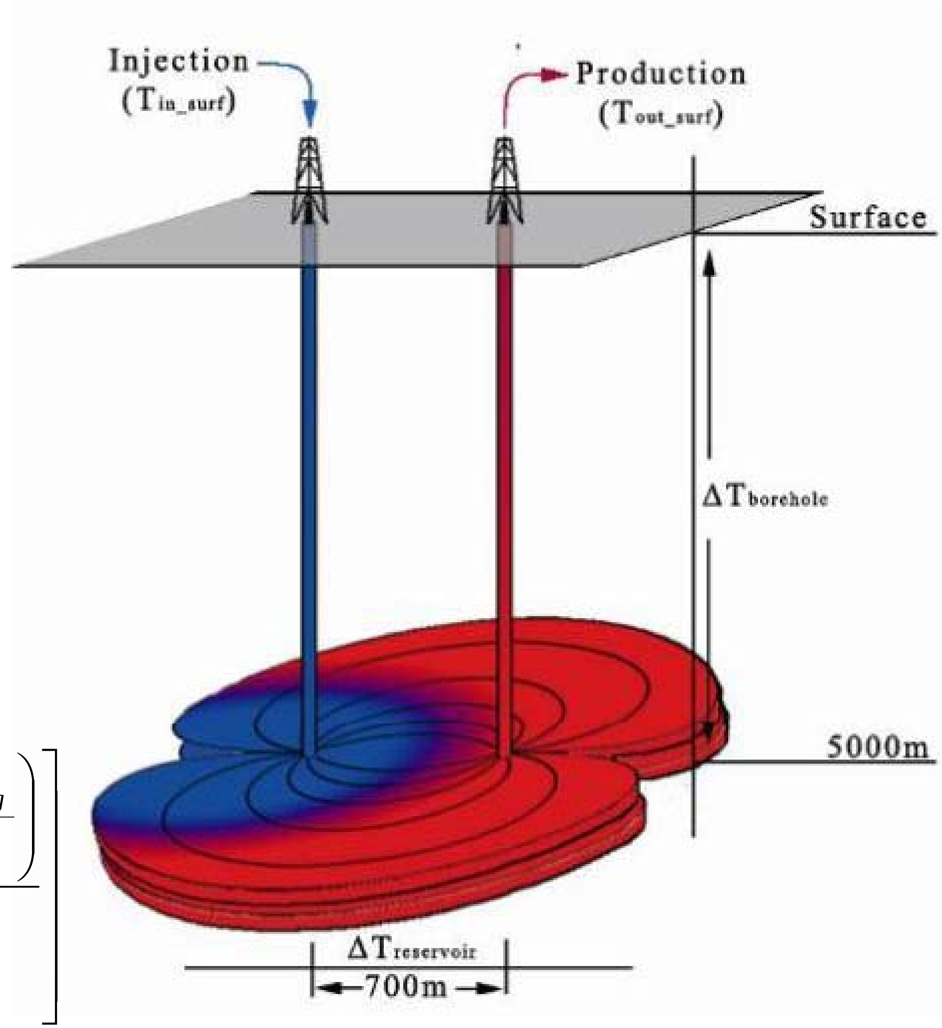
(www.soultz.net)

Subsurface Heat exchanger relies on fracture

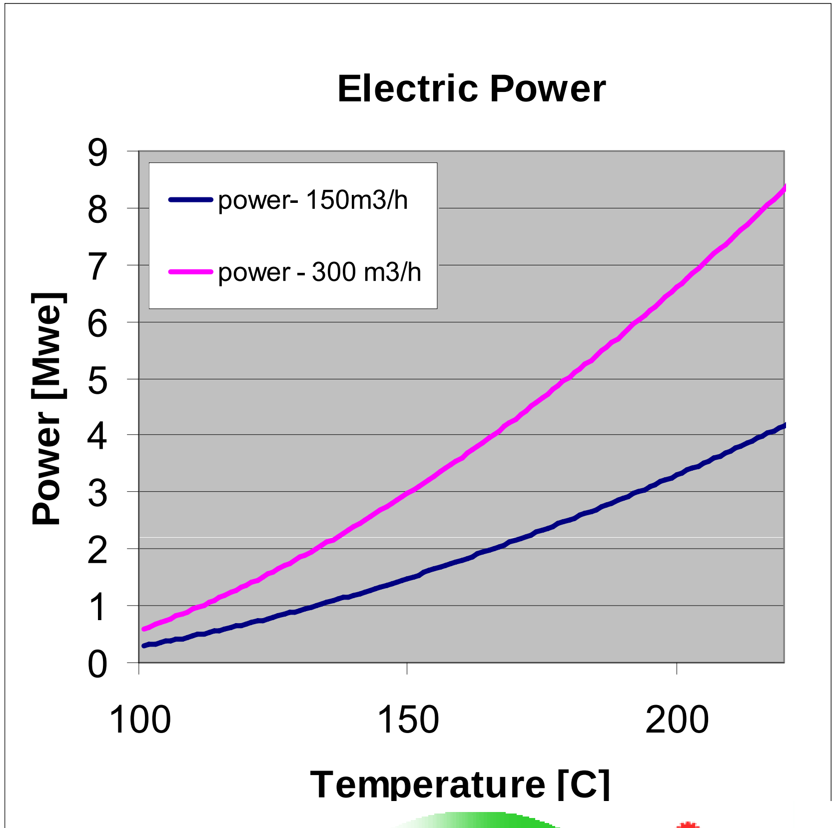
Streamline approach
for fracture flow (Pruess and Bodvarsson, 1983; Heidinger et al., 2006)

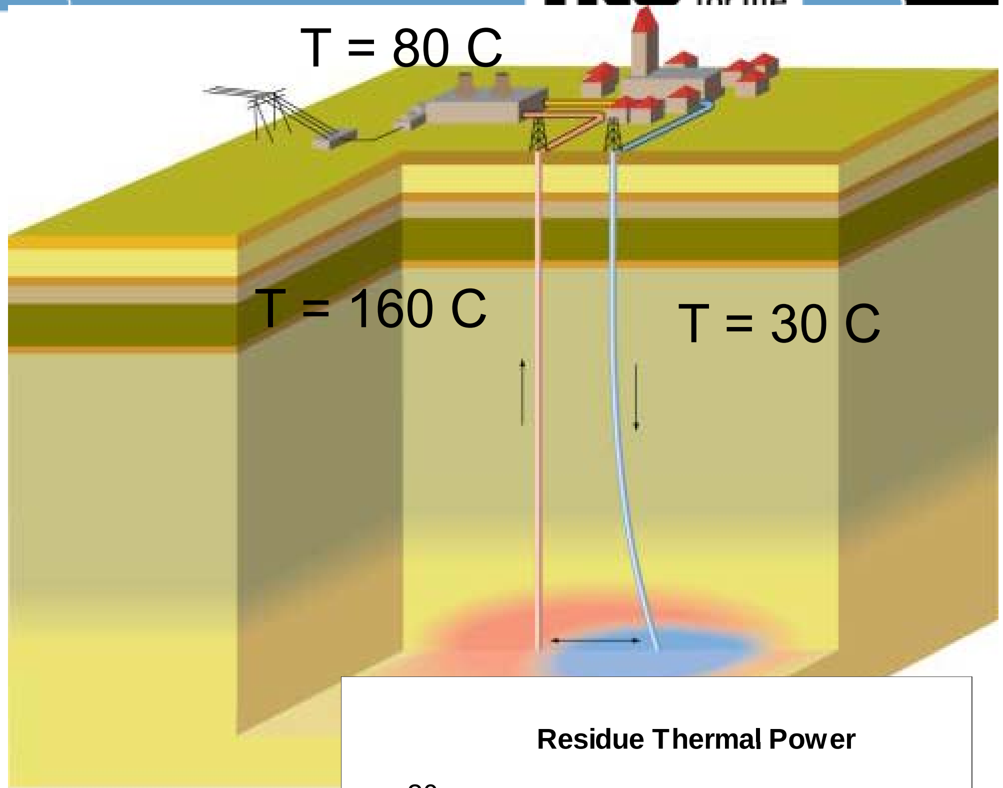
Area of fractures (A) and flow rate (Q) and Number of fractures (N) primarily relate to the sustainibility in time of the high temperatures.

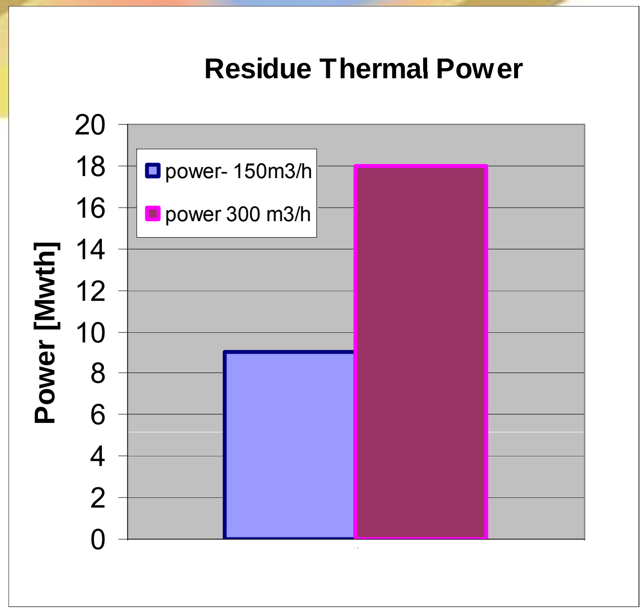
$$T_{out\_res} = T_G - (T_G - T_{in\_res}) erfc\left[\frac{\frac{\sqrt{c_G \lambda_G \rho_G}}{c_F} \left(\frac{Narea_{Seg}}{(Q_{seg})} \right)}{\sqrt{t - tdel}} \right]$$



Electricity Production
(T, flowrate, depth)

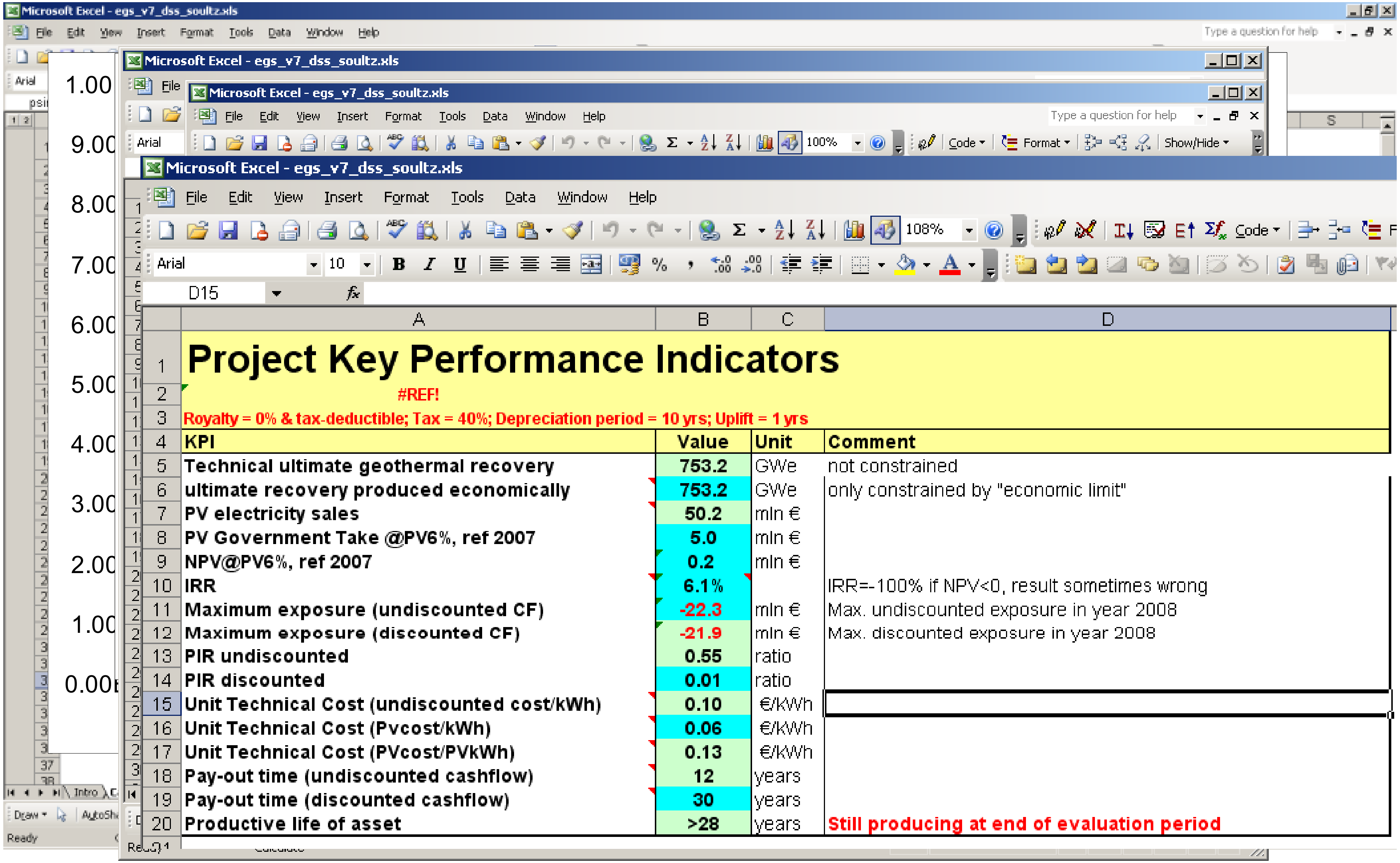






FAST ANALYTICAL MODEL for EGS, EXCEL

http://engine.brgm.fr/DecisionSupportSystem.asp



Project Key Performance Indicators

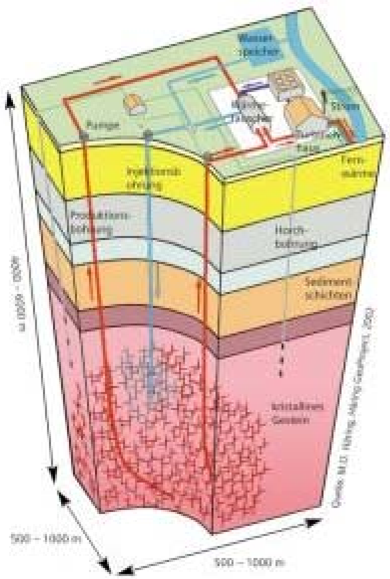
#REF!

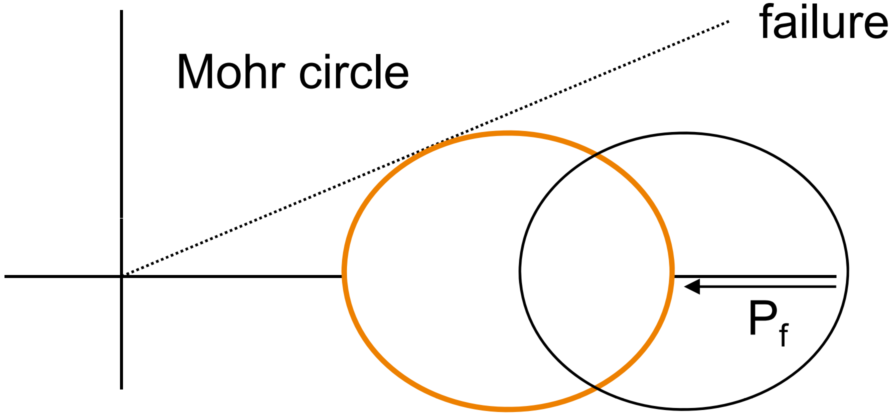
Royalty = 0% & tax-deductible; Tax = 40%; Depreciation period = 10 yrs; Uplift = 1 yrs

KPI	Value	Unit	Comment
Technical ultimate geothermal recovery	753.2	GWe	not constrained
ultimate recovery produced economically	753.2	GWe	only constrained by "economic limit"
PV electricity sales	50.2	mln €	
PV Government Take @PV6%, ref 2007	5.0	mln €	
NPV@PV6%, ref 2007	0.2	mln €	
IRR	6.1%		IRR=-100% if NPV<0, result sometimes wrong
Maximum exposure (undiscounted CF)	-22.3	mln €	Max. undiscounted exposure in year 2008
Maximum exposure (discounted CF)	-21.9	mln €	Max. discounted exposure in year 2008
PIR undiscounted	0.55	ratio	
PIR discounted	0.01	ratio	
Unit Technical Cost (undiscounted cost/kWh)	0.10	€/kWh	
Unit Technical Cost (Pvcost/kWh)	0.06	€/kWh	
Unit Technical Cost (PVcost/PVkWh)	0.13	€/kWh	
Pay-out time (undiscounted cashflow)	12	years	
Pay-out time (discounted cashflow)	30	years	
Productive life of asset	>28	years	Still producing at end of evaluation period

Mechanisms of induced seismicity in EGS

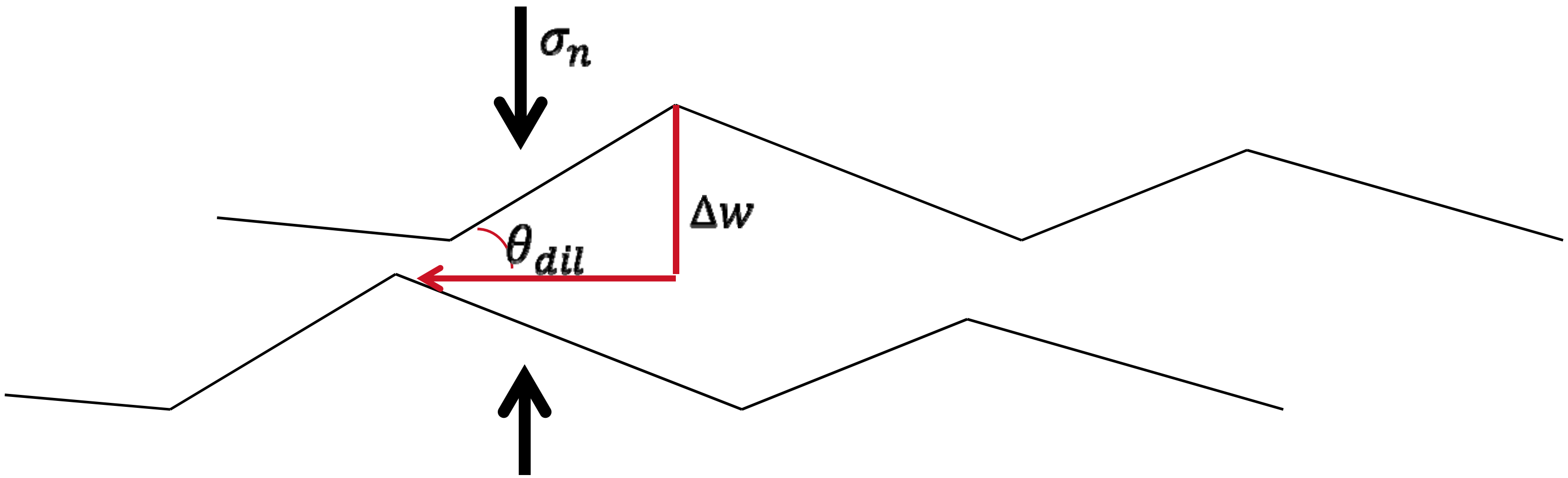
- Mechanisms of shear failure (Majer et al., 2007)
  - Pore pressure ↑ Effective normal stress ↓
  - Temperature ↓ → contraction → reduction of static friction
  - Injected volume → stress perturbation
  - Chemical reaction may reduce coefficient of friction





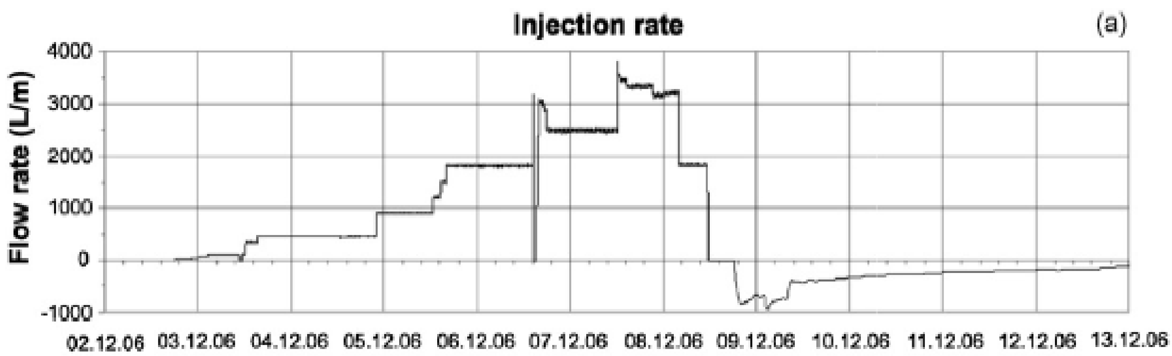
Sollicited Induced seismicity

- EGS operations relies on generating permeability through **shear fractures.**

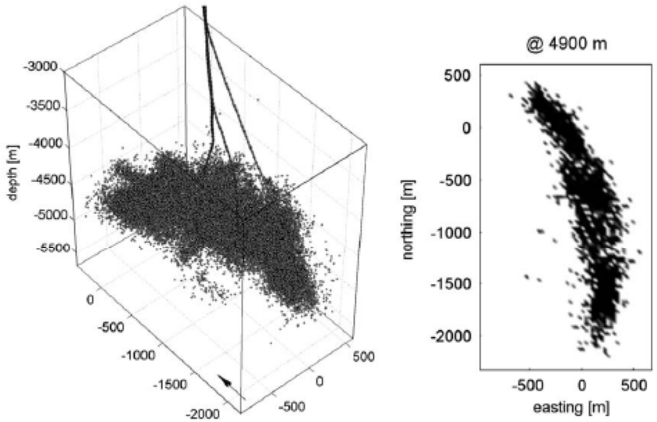


- **Through massive fluid injection typically 50l/s over various days**

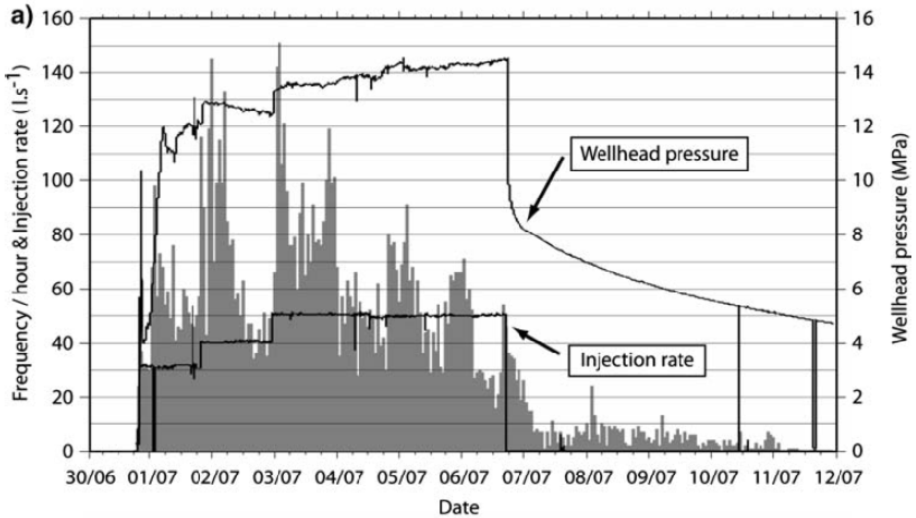
Basel injection rate



Seismicity in EGS reservoirs – related to shear faulting



GPK 2 stimulation, Baisch et al., 2010

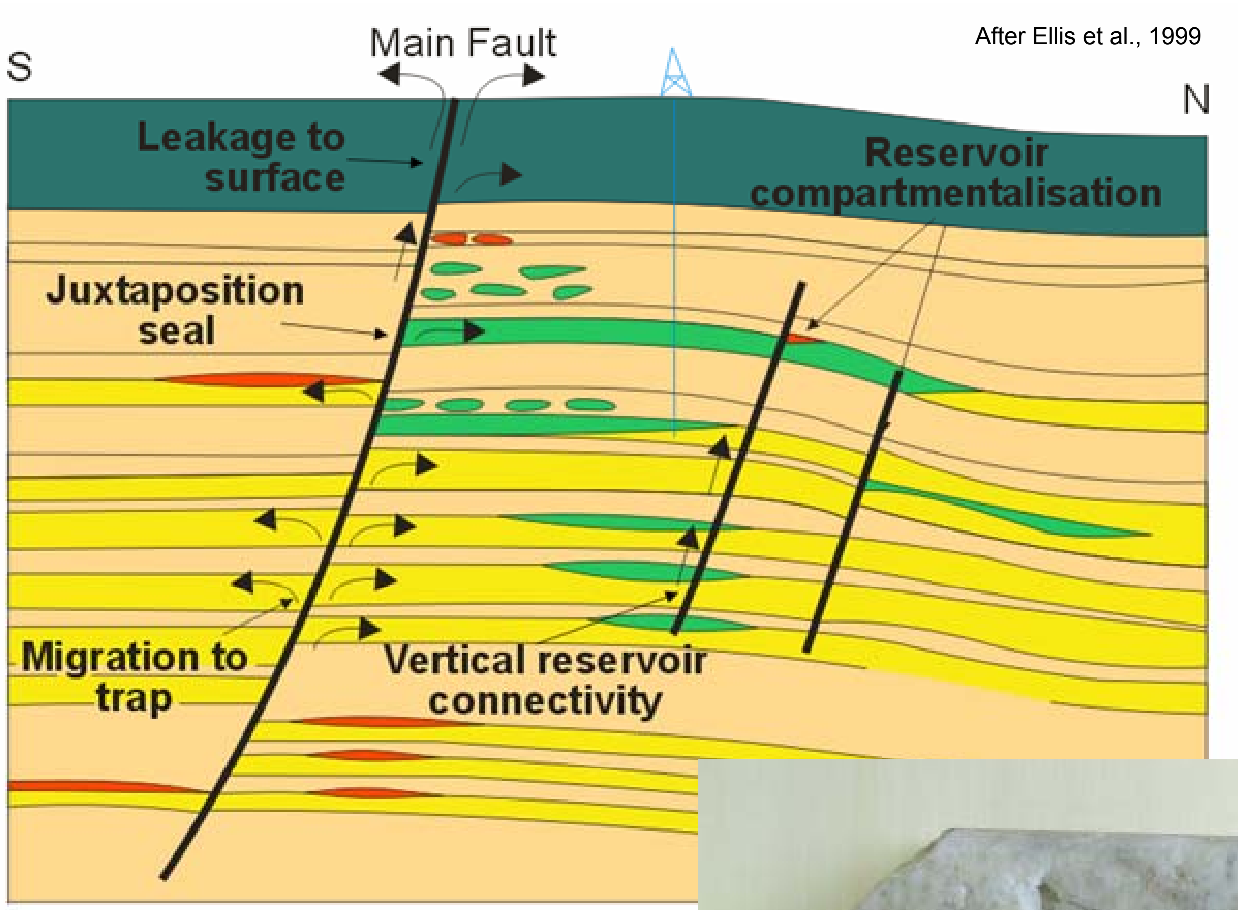


GPK 2 ,Cuenot et al., 2008

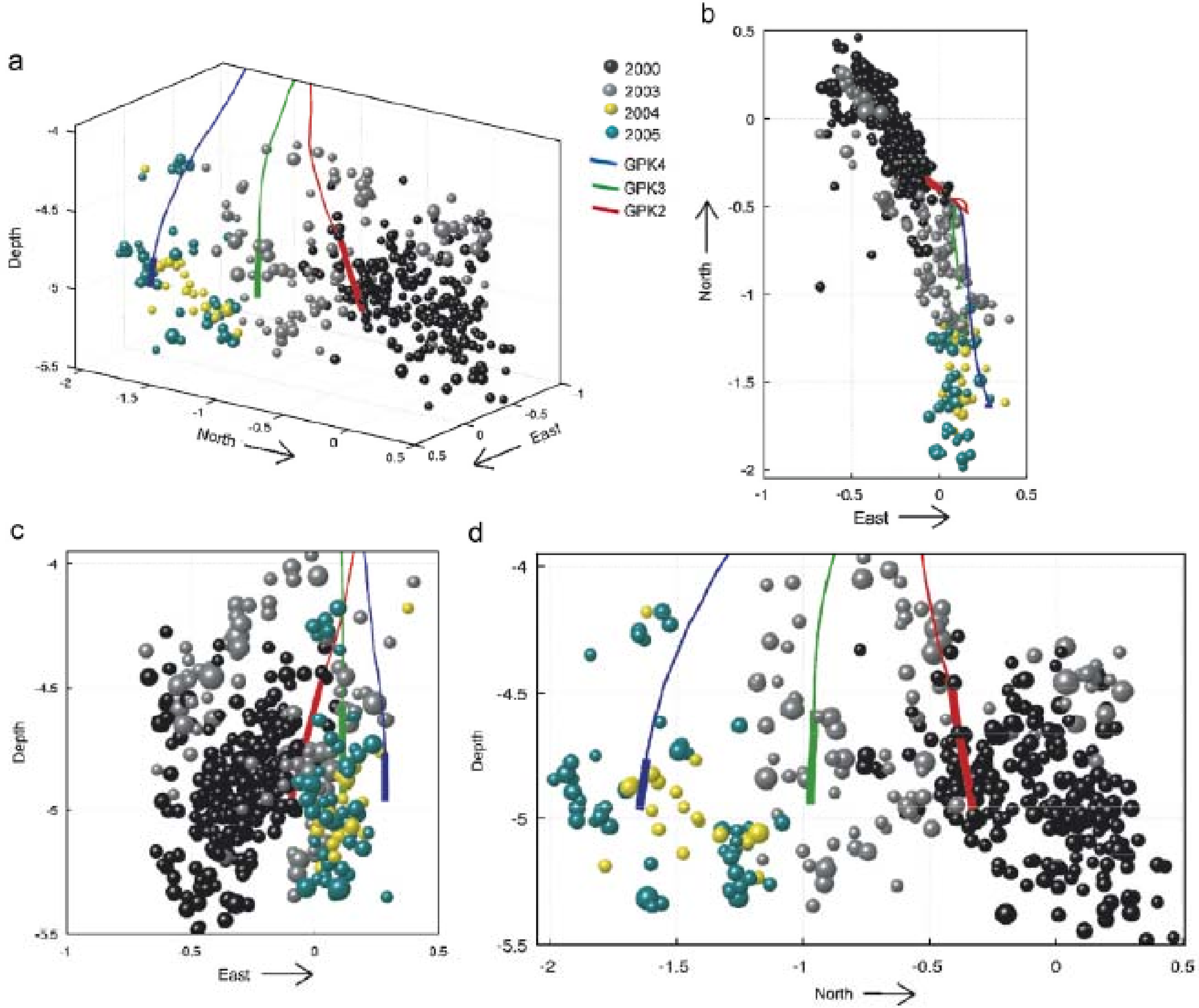
- Starts immediately after injection
- Cloud reaches ~100 m in a few days
- Pre-existing tectonic features large influence (alignment of seismic cloud)
- 100’s -100,000’s of events
- 90% M_L<1 …
- … but a few ‘large’ events
  - Soultz: M 2.9, Basel M 3.4
- Seismic activity dependent on injection
- After injection stops, seismicity decays gradually

- Flow rates in the order of 20l/s

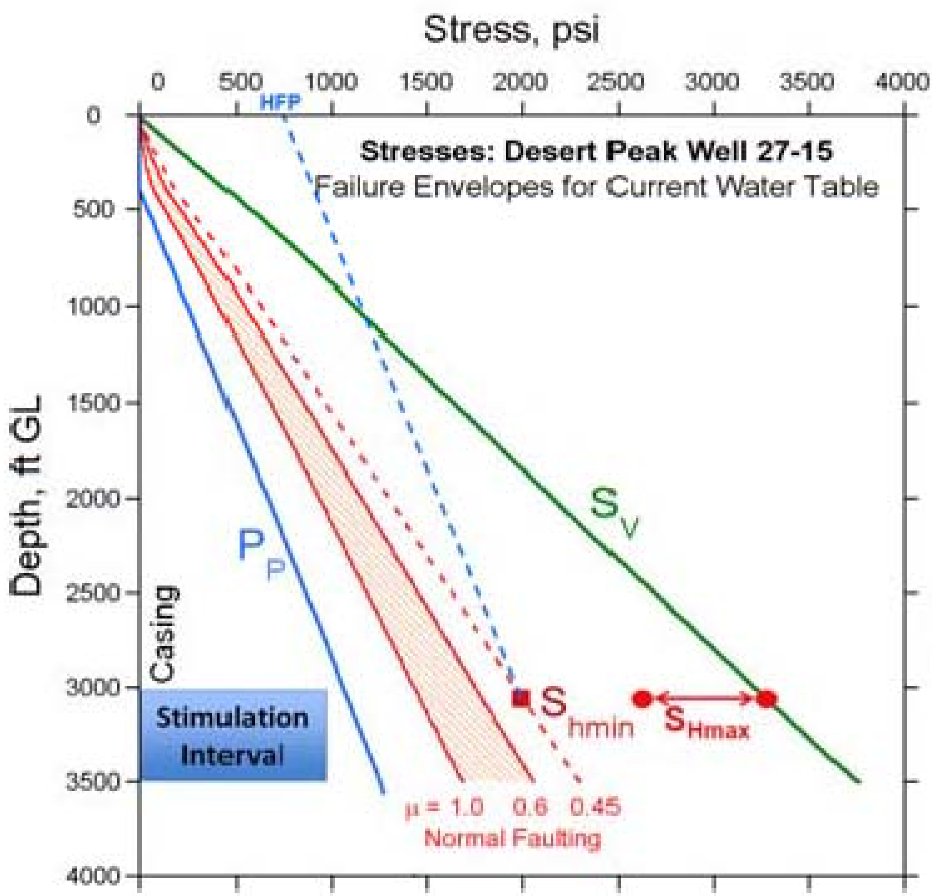
Active faults allow hydro-thermal conduit zones



Soultz, core of fault zone
4 km depth (HAFZ)


a
2000
2003
2004
2005
GPK4
GPK3
GPK2
Depth
North
East
b
North
East
c
Depth
East
d
Depth
North

Stress characterization (minifrac or Leak off pressure)



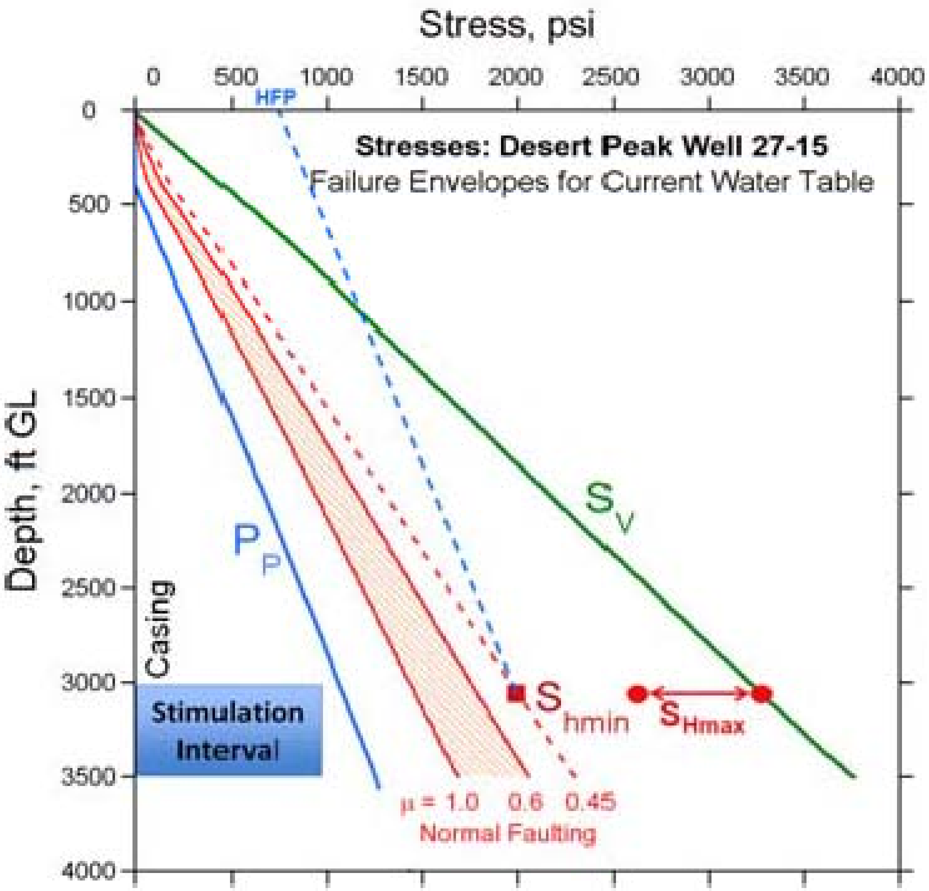
Extensional setting

Sv = effective burial stress

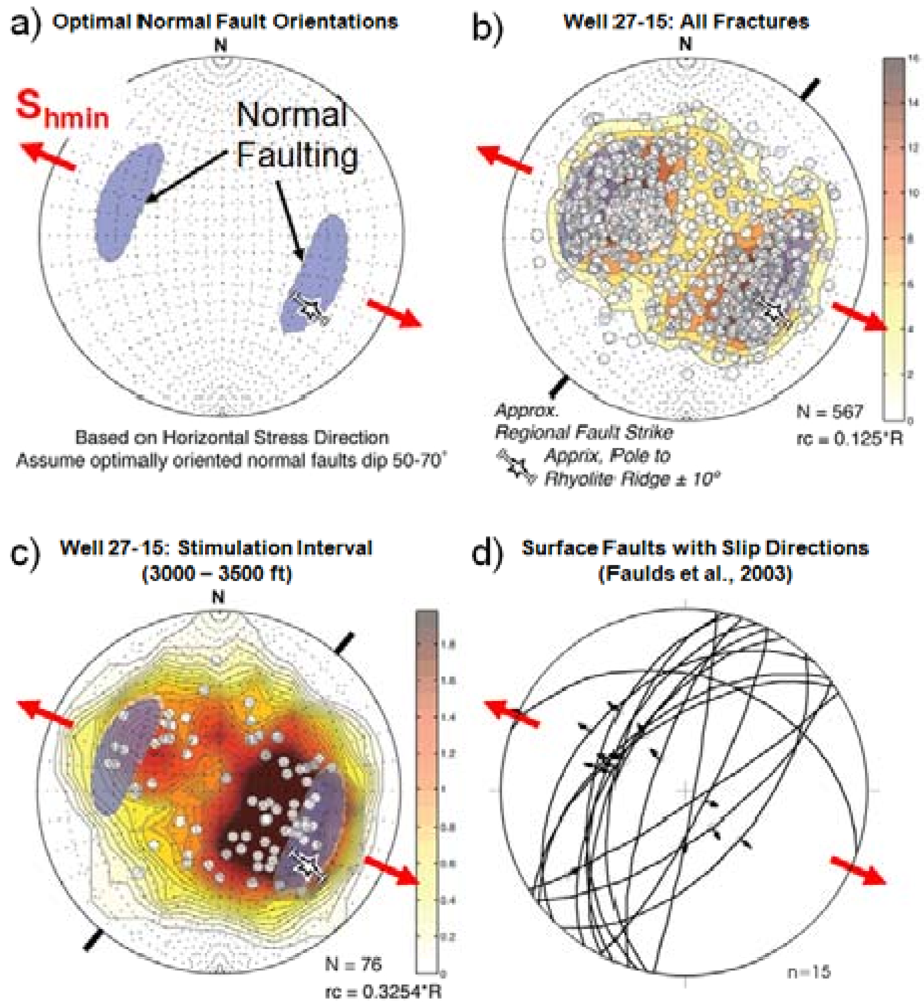
Figure 3: Magnitude of the least horizontal principal stress, S_{himn}, from the minifrac in well 27-15. The vertical stress, S_V, and formation fluid pressure, P_p, were calculated as described in the text. The dashed lines indicate the range of S_{himn} at which frictional failure would be expected on optimally oriented normal faults for coefficients of friction, μ, ranging from 0.6 to 1.0. The dashed blue line is the borehole pressure (at ambient formation temperatures and fluid densities) at which a hydraulic fracture should start to propagate at the top of the planned EGS stimulation interval, corresponding to a wellhead hydrofrac pressure (HFP) of ~750 psi.

Hickman and davatzes, 2010

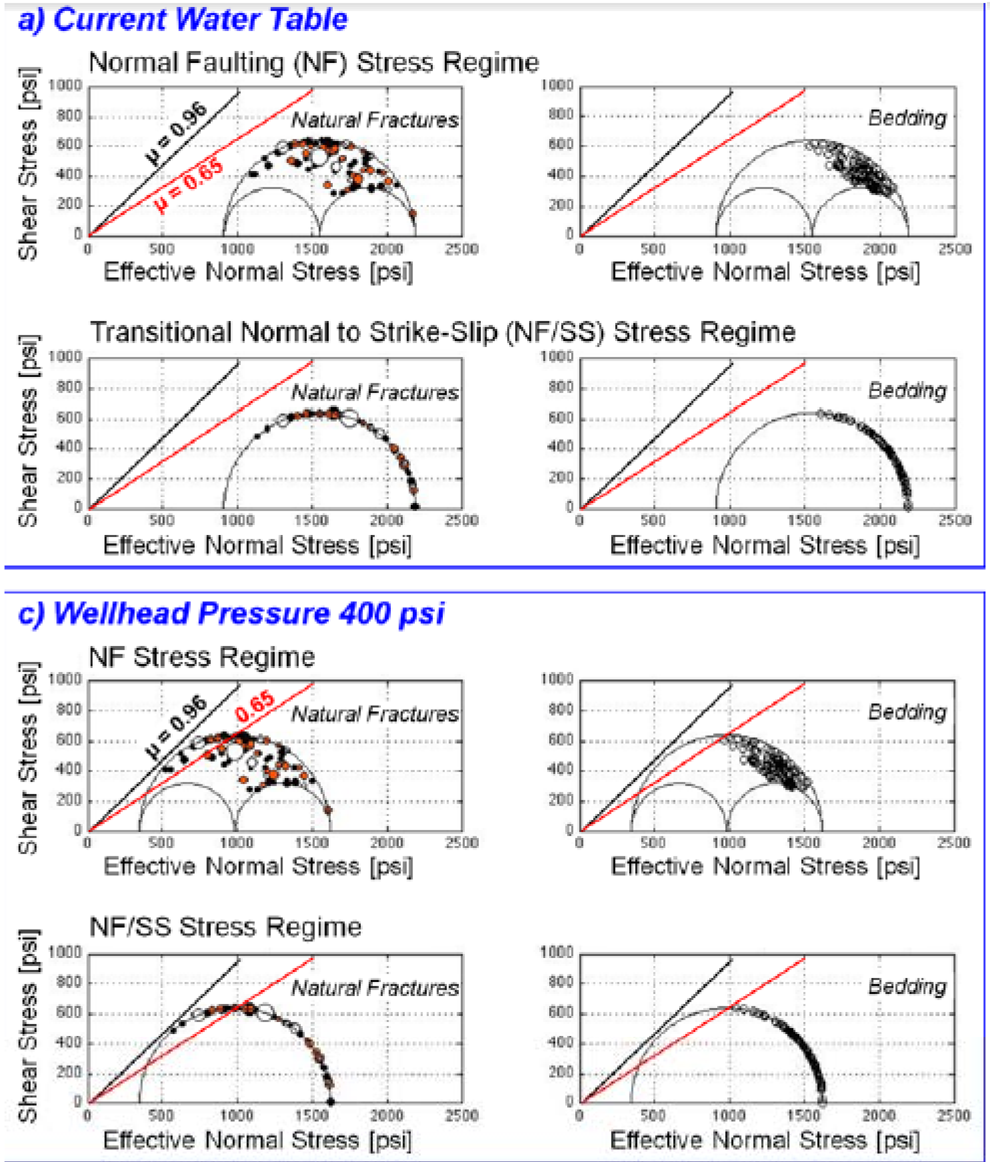
Stress characterization (minifrac)



fracture characterization (outcrop, fmi)

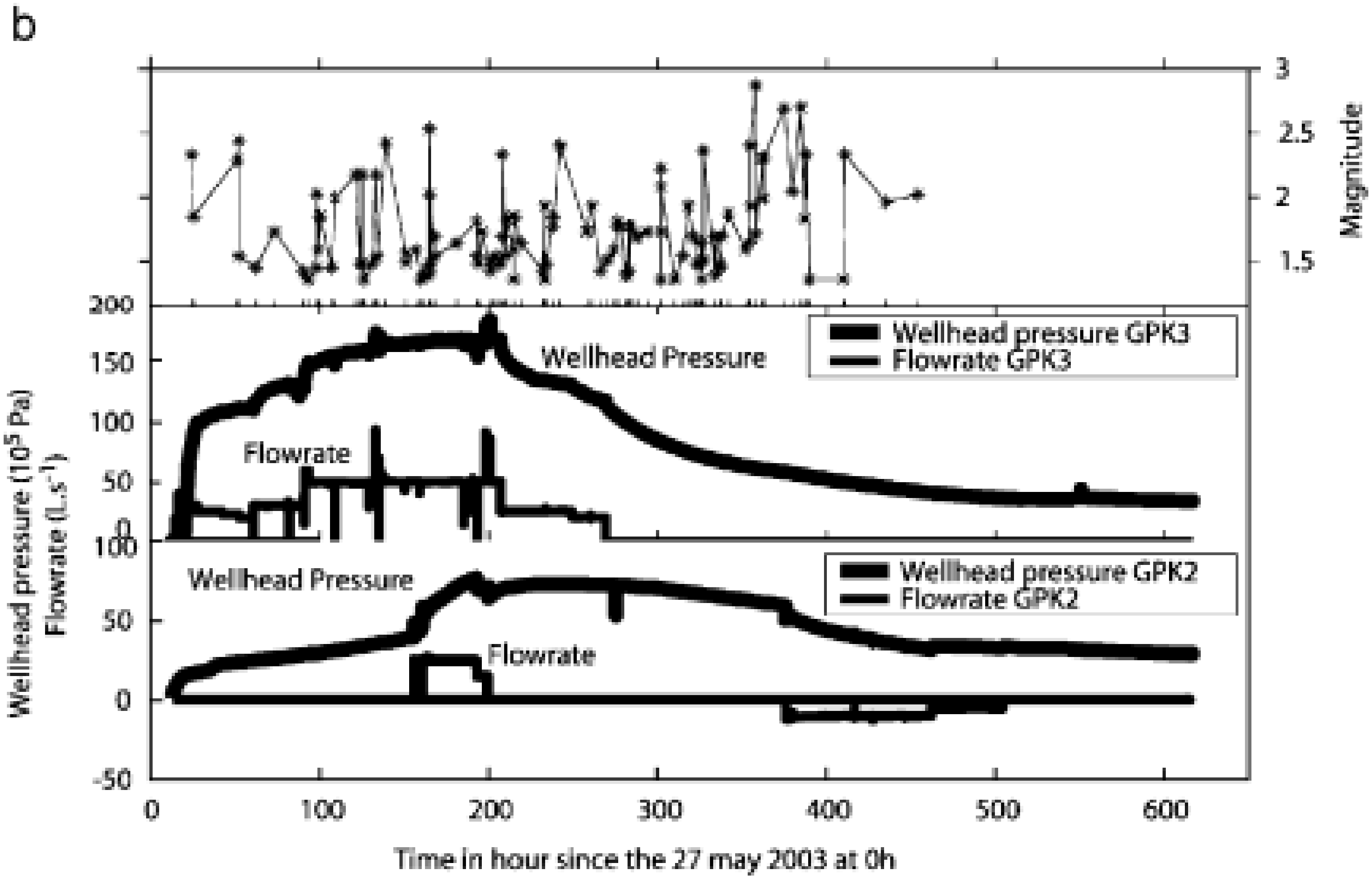


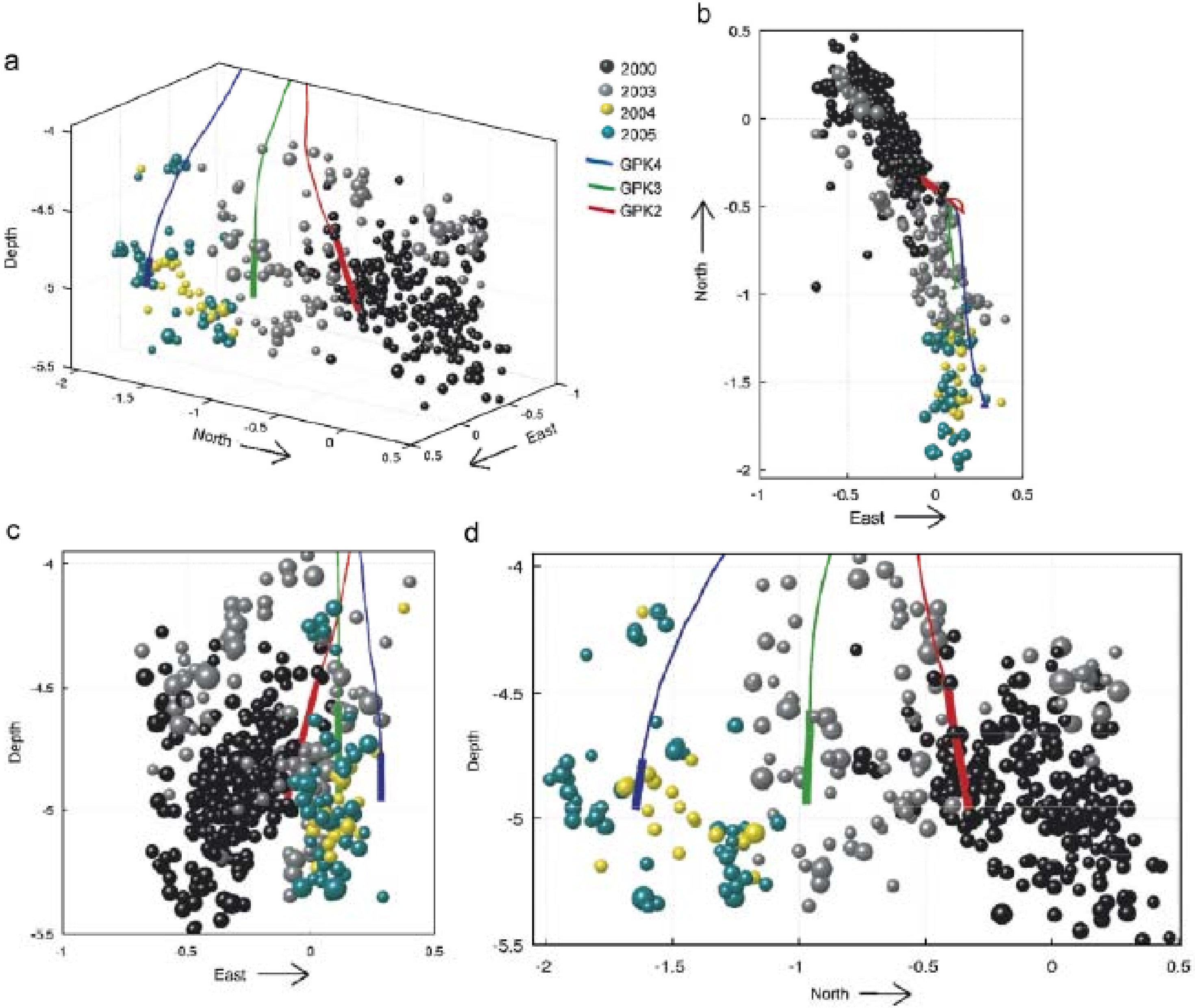
Hickman and davatzes, 2010



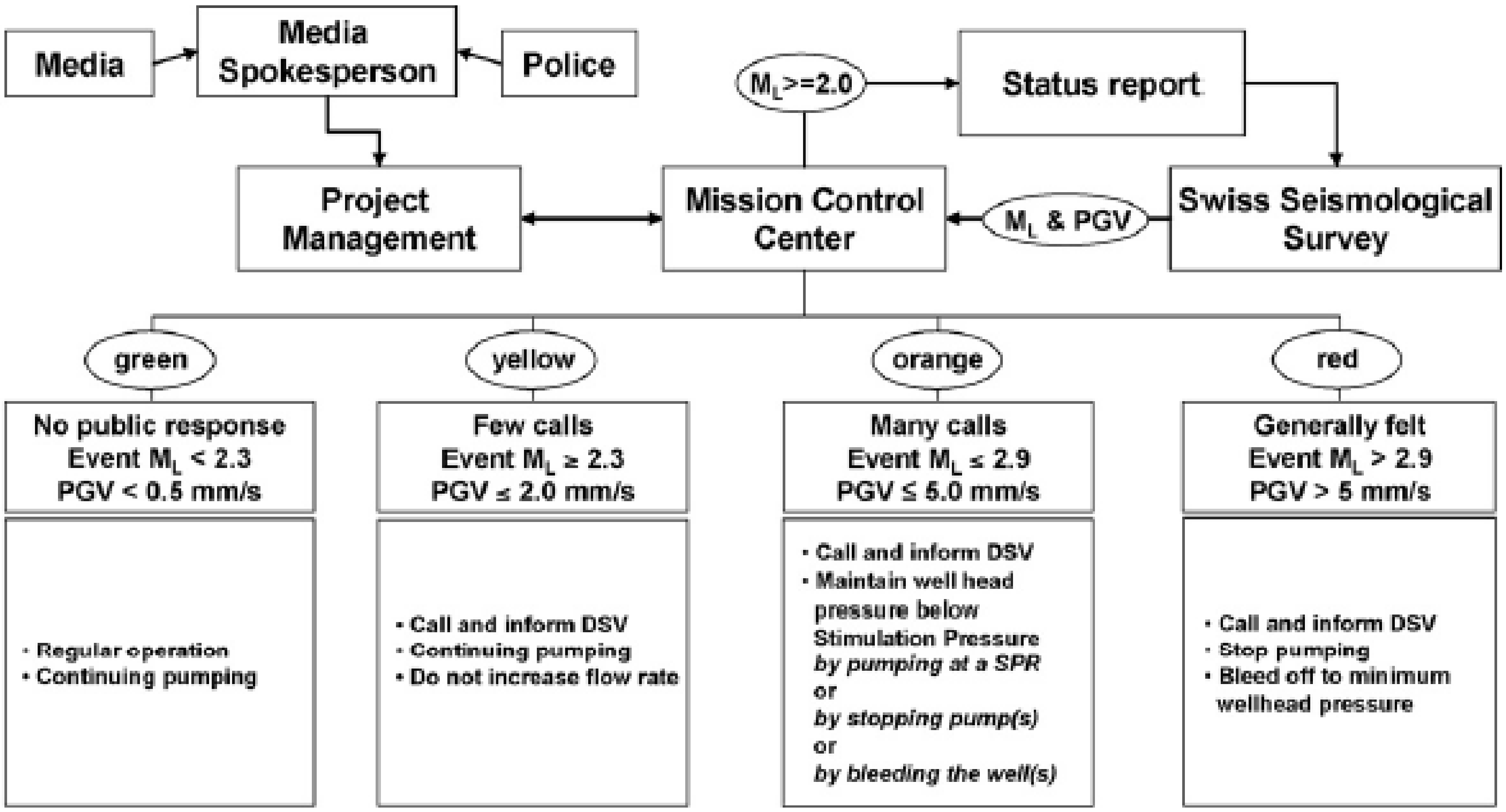
At current fluid pressures, analysis of the propensity for frictional failure shows that both natural fractures and bedding/foliation should be frictionally stable within the planned stimulation interval, for either a NF or NF/SS stress regime (Figure 5a). This agrees with the previous observation that differential stress (S_V - S_{hmin}) at this location is too low to result in pervasive frictional failure on optimally oriented normal faults for typical laboratory friction values (Figure 3). However, as the ambient water level in well 27-15 is raised and wellhead pressures increased from 200 to 400 and finally to 600 psi, this analysis shows that more and more fractures within the stimulation interval fall within the frictional failure envelope bounded by the lines for μ= 0.65 and 0.96 (Figures 5 b, c and d). By the time a wellhead pressure of 600 psi is reached, a significant number of the natural fractures within the stimulation interval fall within or beyond this failure envelope (Figure 5d), suggesting widespread frictional failure. By plotting the ratio of shear to effective normal stress on fractures as a function of depth for a wellhead pressure of 600 psi, it can be seen that the greatest density of fractures with a high tendency for slip (especially large-aperture fractures) exists within the siliceous rhyolites above about 3300 ft GL (Figure 6).

Soultz – maximum Magnitude 2.9 in GPK3 stimulation



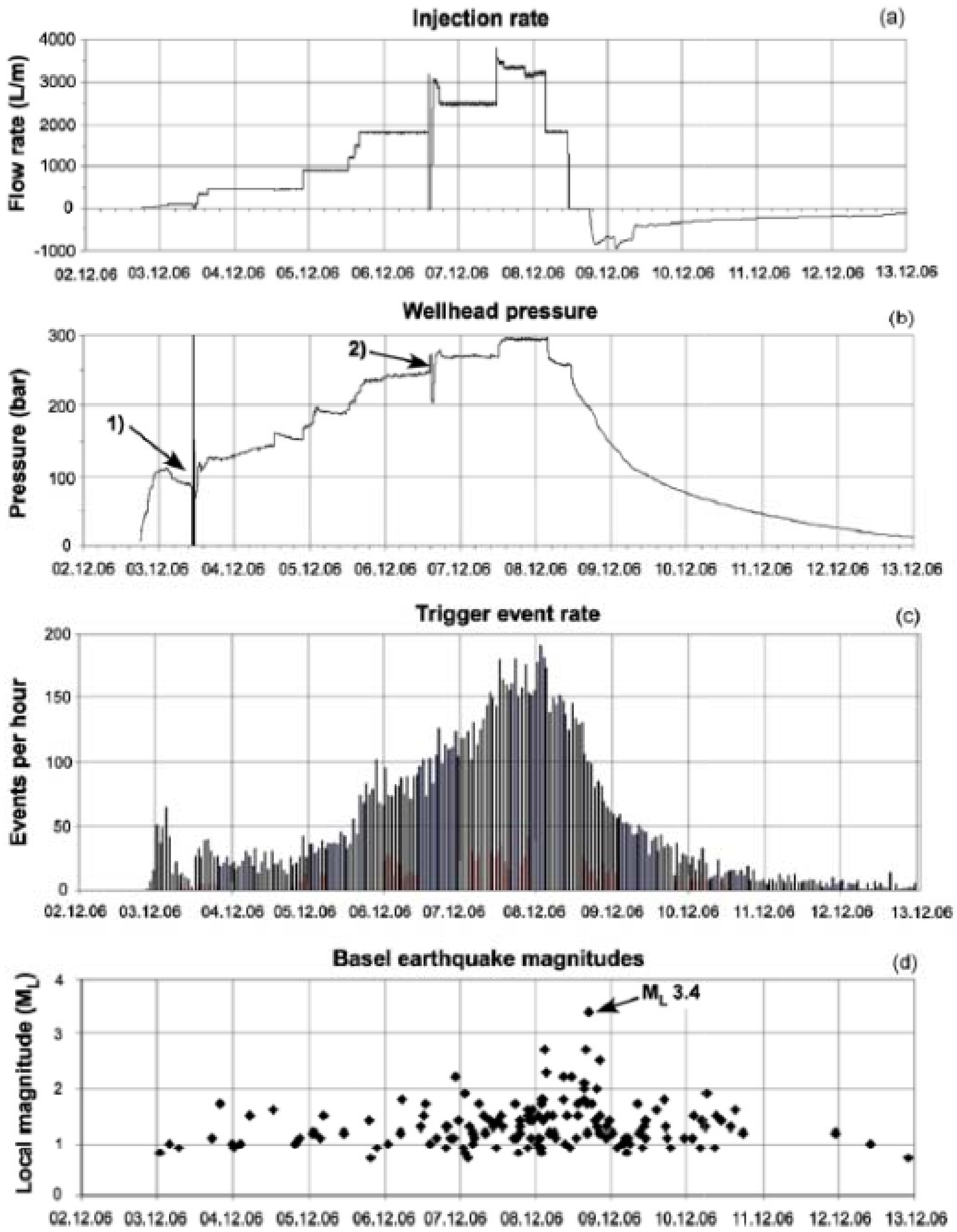

a
b
c
d
2000
2003
2004
2005
GPK4
GPK3
GPK2
Depth
North
East
-4
-4.5
-5
-5.5
-2
-1.5
-1
-0.5
0
0.5
1

(Static) Traffic light system basel



BASEL

- Very similar as Soultz
- However M_L>2.9 so shut-in
- After shut-in M_L=3.4 occured



Haering et al., 2008

This posed a major problem…..

- Over 6 mln damage claims
- Project developer had promised M_L<3
- Largest historic EQ north of the alps (estimated M=7) occurred close to Basel in 1356 and destroyed the city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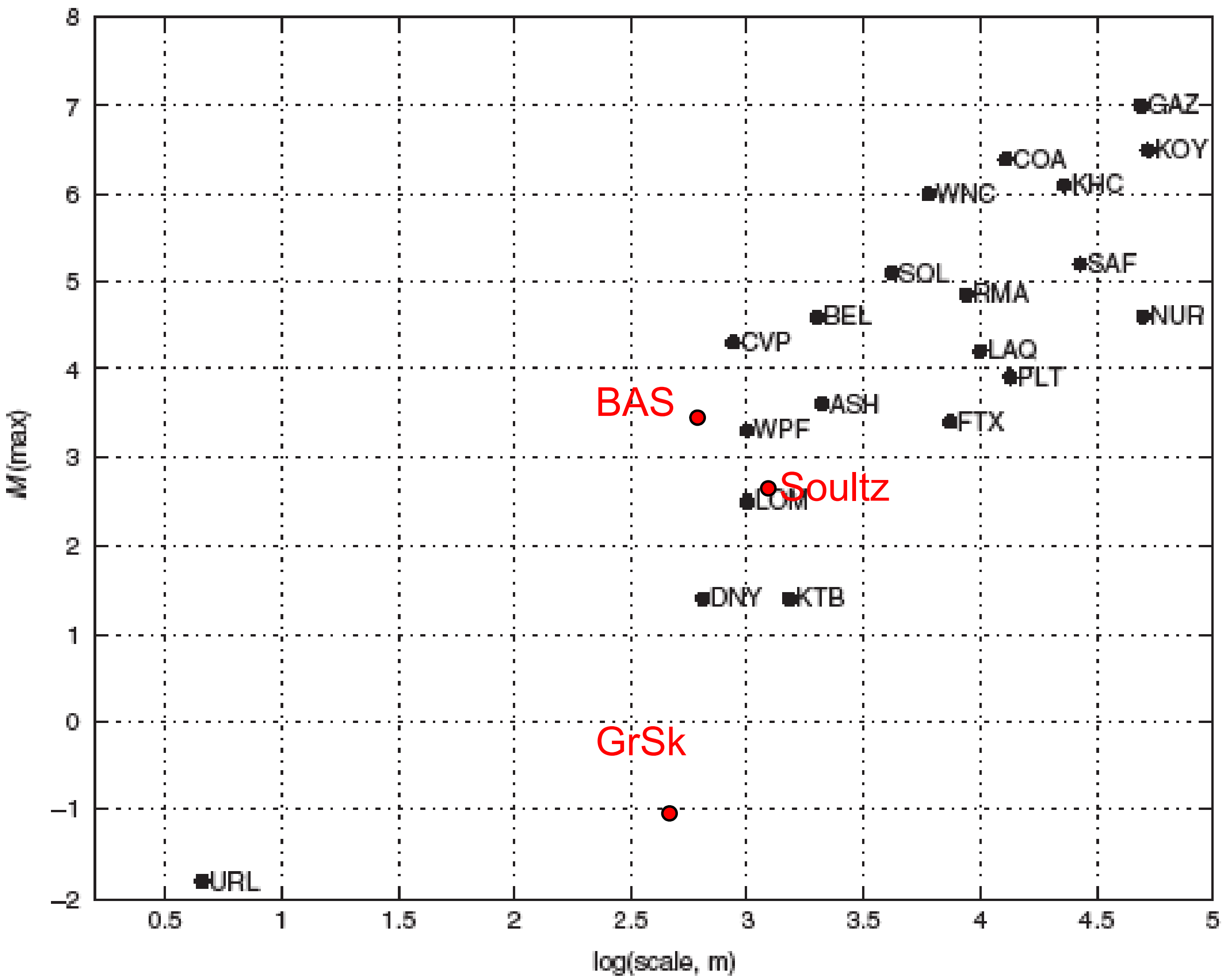
News › World news › Switzerland

Swiss geothermal power plan abandoned after quakes hit Basel

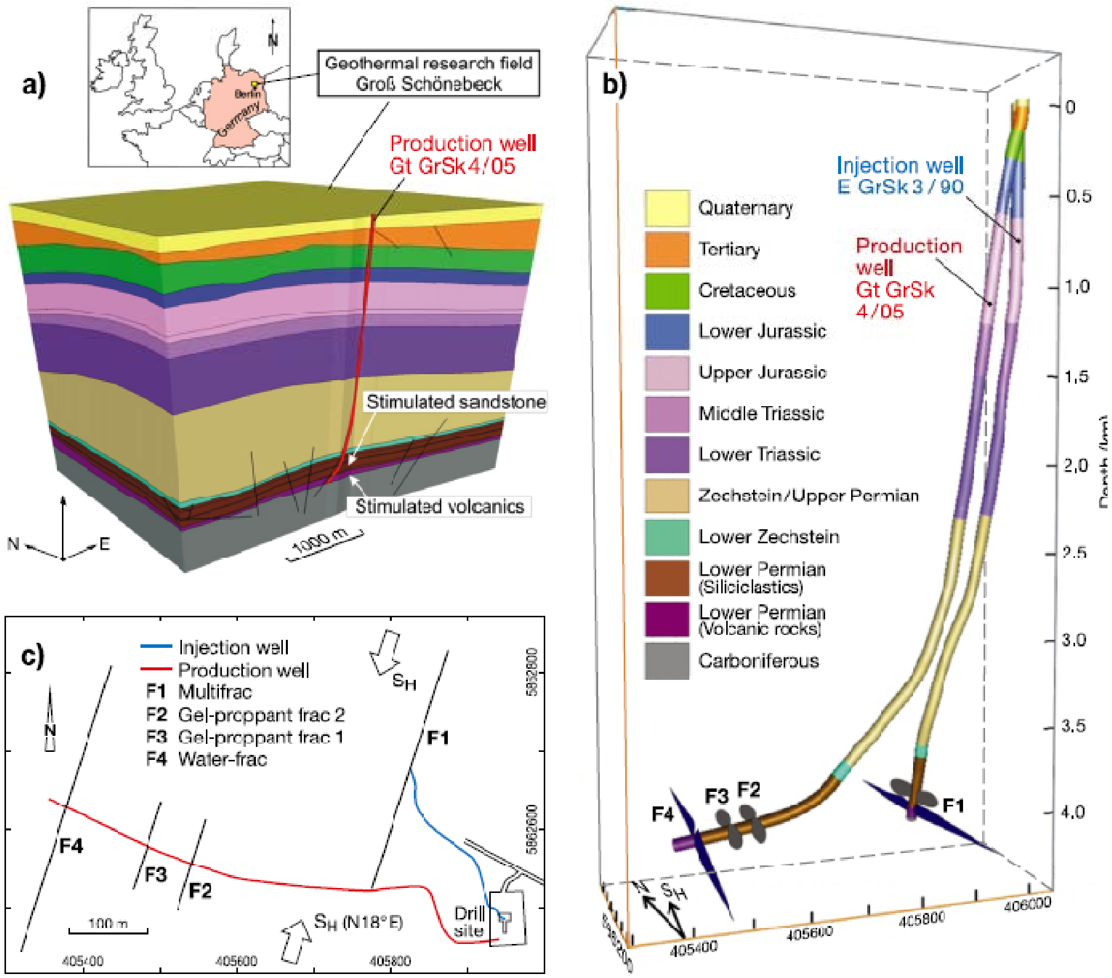
Designer of 'hot rocks' scheme under city on a fault line could face jail over damage to property

Can we make more reliable EGS?

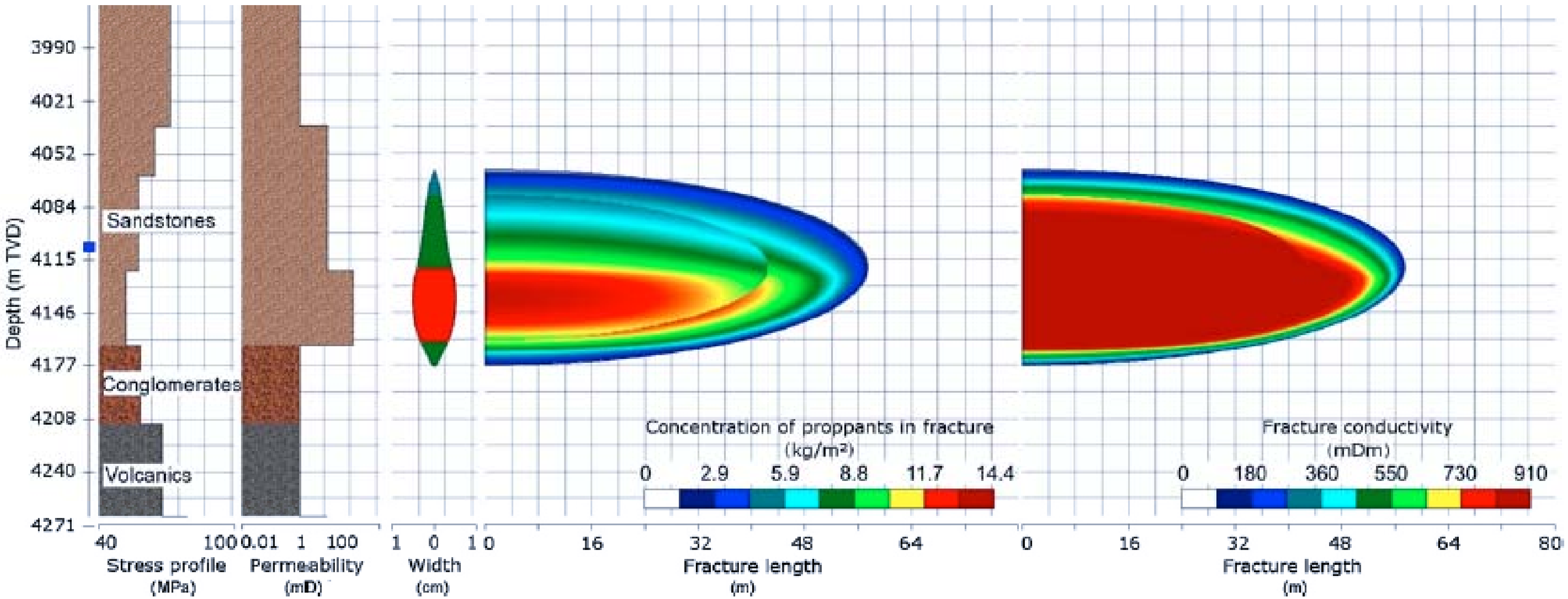


The stress magnitudes in the Dethlingen sandstone at 4.1 km depth were determined to be S_V=78 - 100 MPa from density logs, S_H=98 MPa (at N18E) estimated from transitional form of stress regime from normal faulting to strike slip faulting, and S_h=55 MPa from leak-off tests in both wells. In the volcanic section, mainly the minimal principal horizontal stress is different and is equal to S_h=72 MPa.

During stimulation, the strongest microearthquakes (with $M_w \leq -1$) occurred on a pre-existing fault, which theoretically was relatively critically stressed. The strike and dip of this fracture plane are 17°±10° and 52°±10° SE respectively.



G. Zimmermann, A. Reinicke / Geothermics 39 (2010) 70–77



Geothermal **E**ngineering Integrating Mitigation of **I**nduced **SE**ismicity in **R**eservoirs

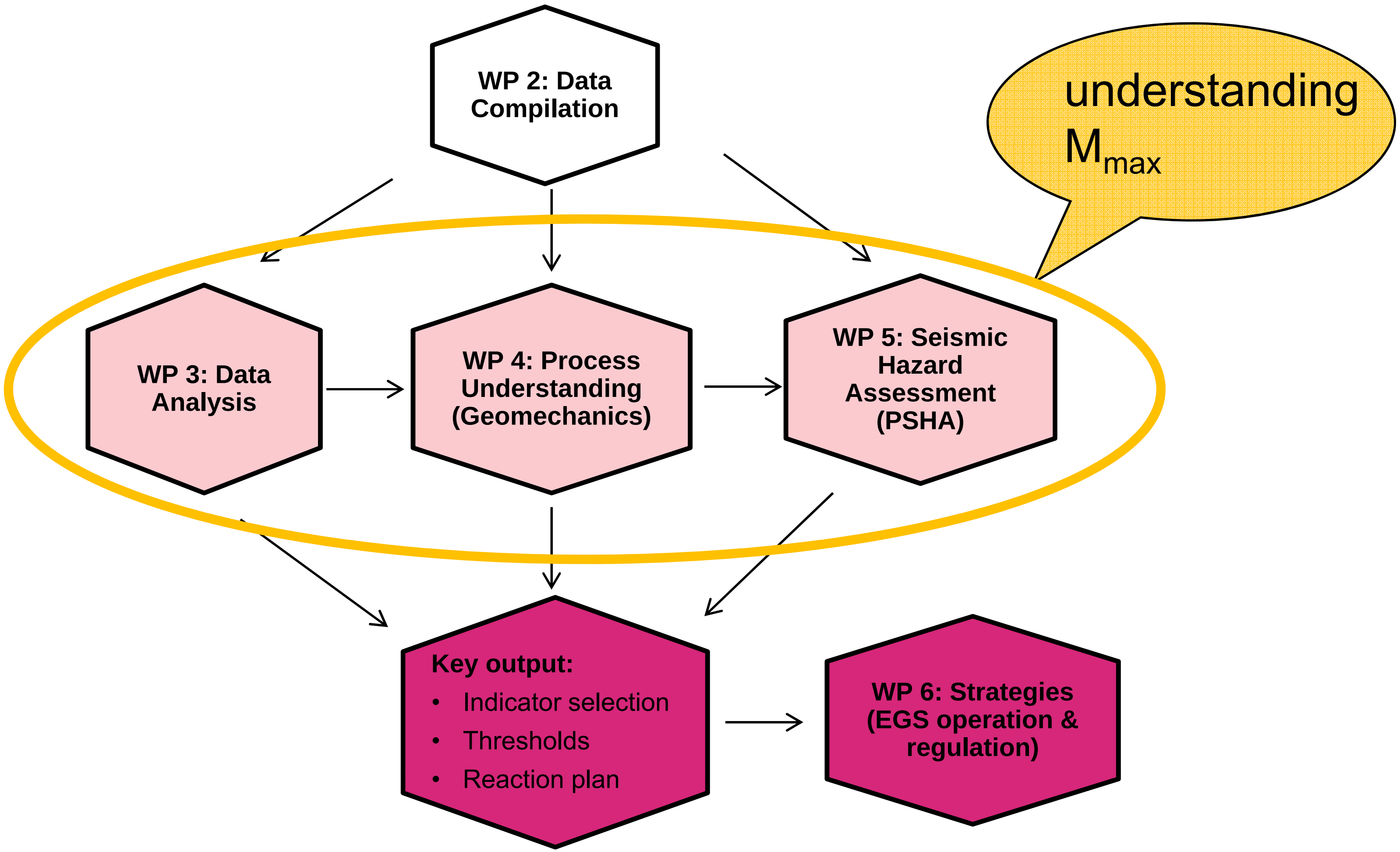
The European GEISER project

David Bruhn (GFZ Potsdam)

Ernst Huenges (GFZ), Kristjan Agustsson (ISOR), Arno Zang (GFZ), Xavier Rachez (BRGM), Stefan Wiemer (ETH), Jan Diederik van Wees (TNO) & Philippe Calcagno (BRGM)

GEISER Project

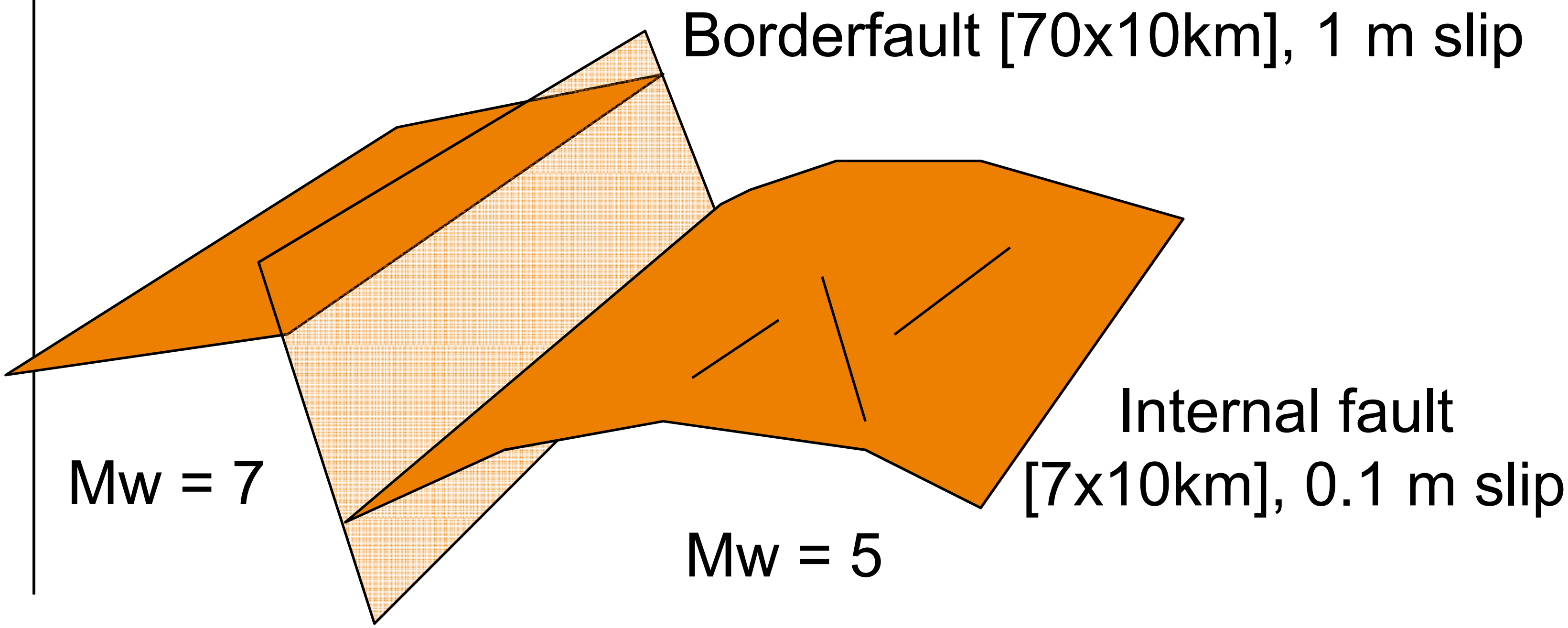
Workflow: Understanding Induced Seismicity



What is the relation with magnitude and surface slip

- Hanks and Kanimori (1979)

$$M_w = 0.67 \log(M0) - 10.7$$

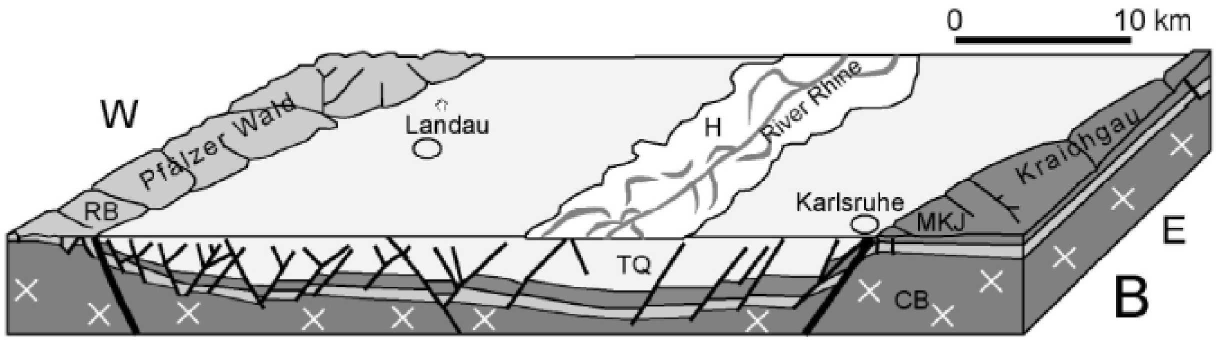


M=7, 70x10 km fault, 1m displacement

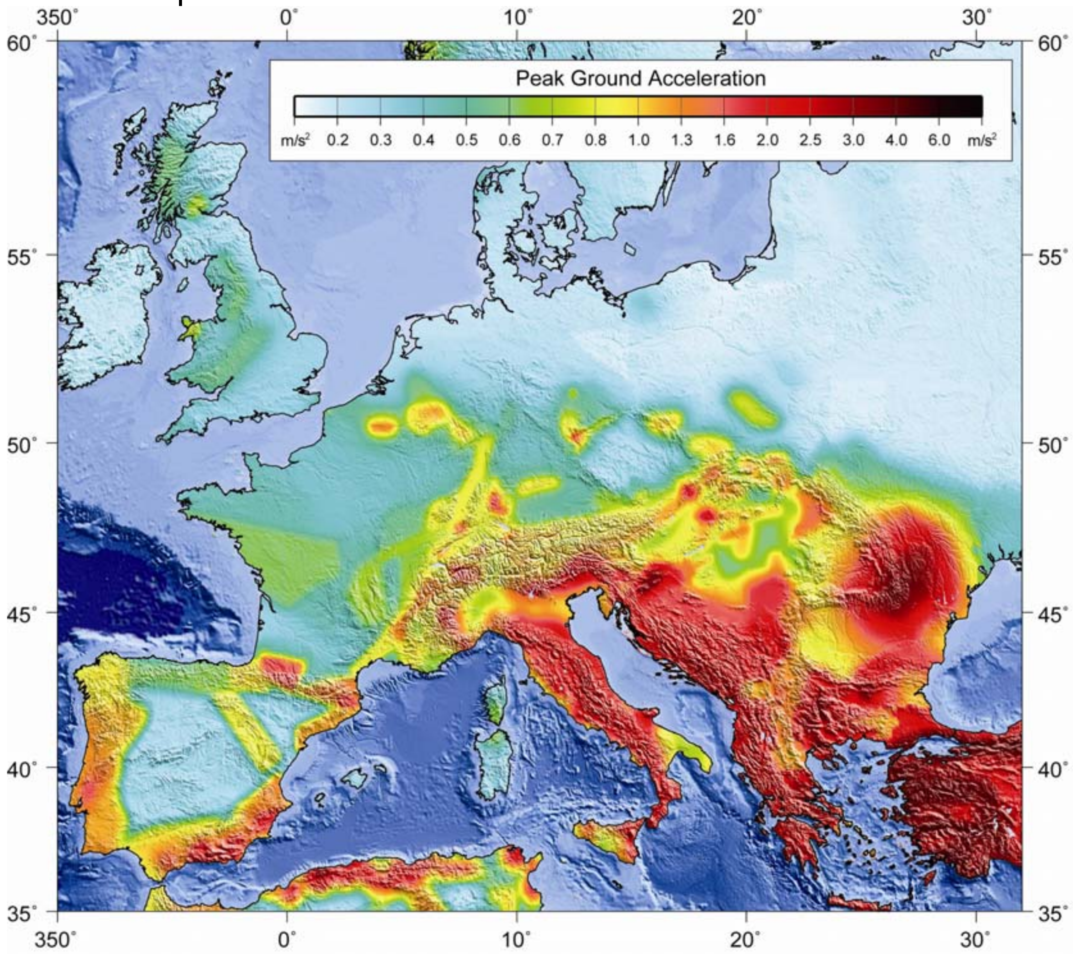
M=6, 30x5 km fault, 0.4m displacement

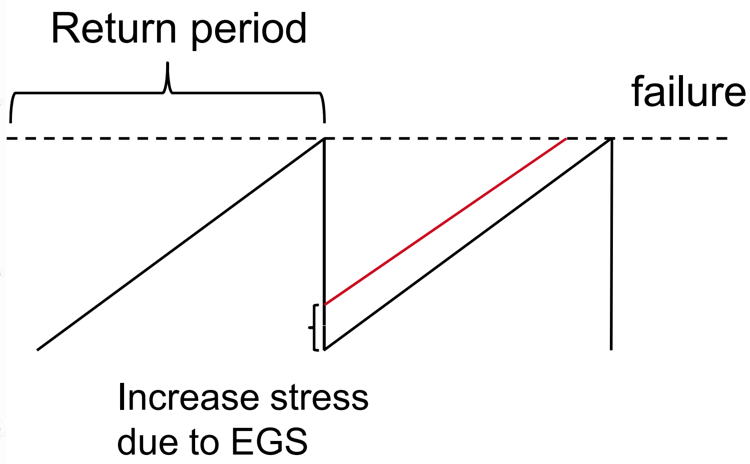
M=5, 15x5 km fault, 0.15m displacement

Big earth quakes
Located at
Mapped Major faults



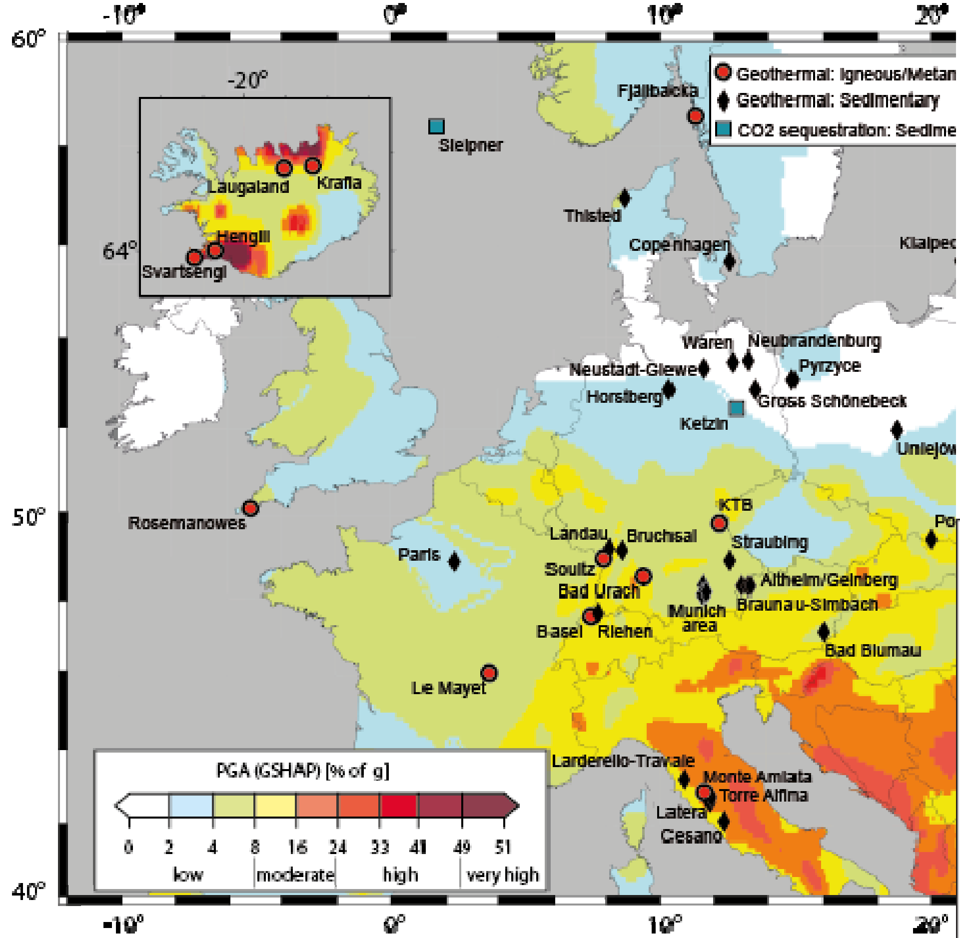
→ stay away from seismically active faults



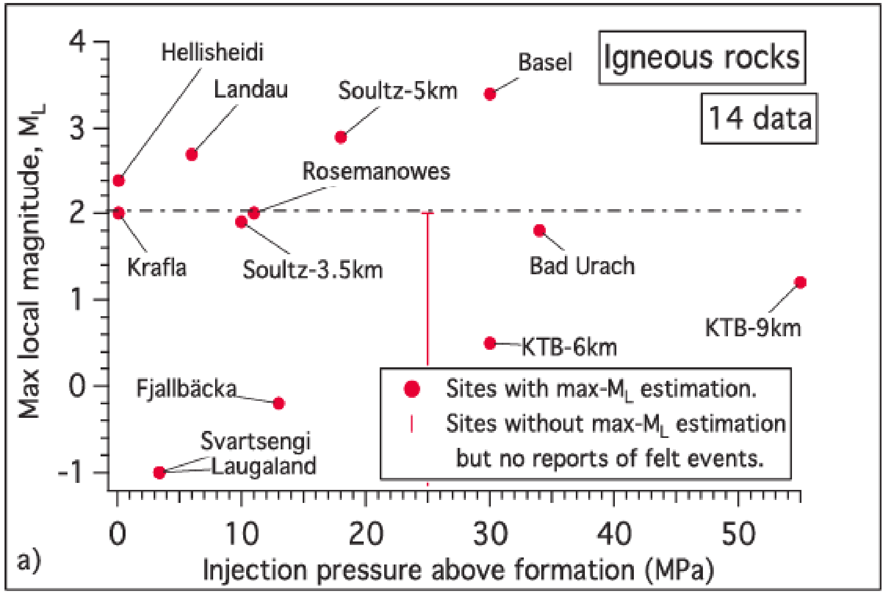


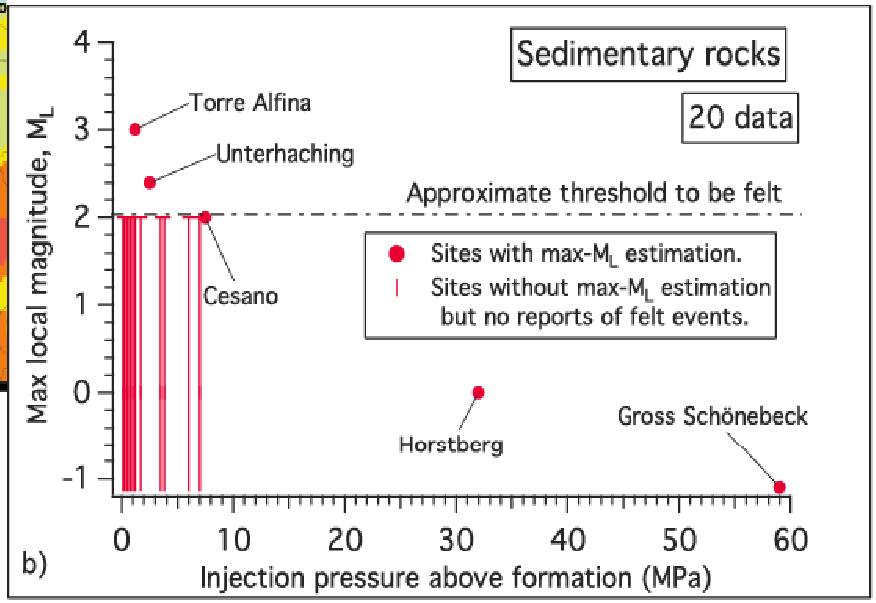
Seismic Hazard Map of Europe as part of the Global Seismic Hazard Map (Giardini et al., 2003; Grünthal et al., 1999). The map depicts the seismic hazard as Peak Ground Acceleration (PGA, ms^{-2}) with 10% probability of exceedence (or a 90% chance of non-exceedance) in 50 years, corresponding to a return period of 475 years (source GFZ, oliver Heidbach)

Data analysis

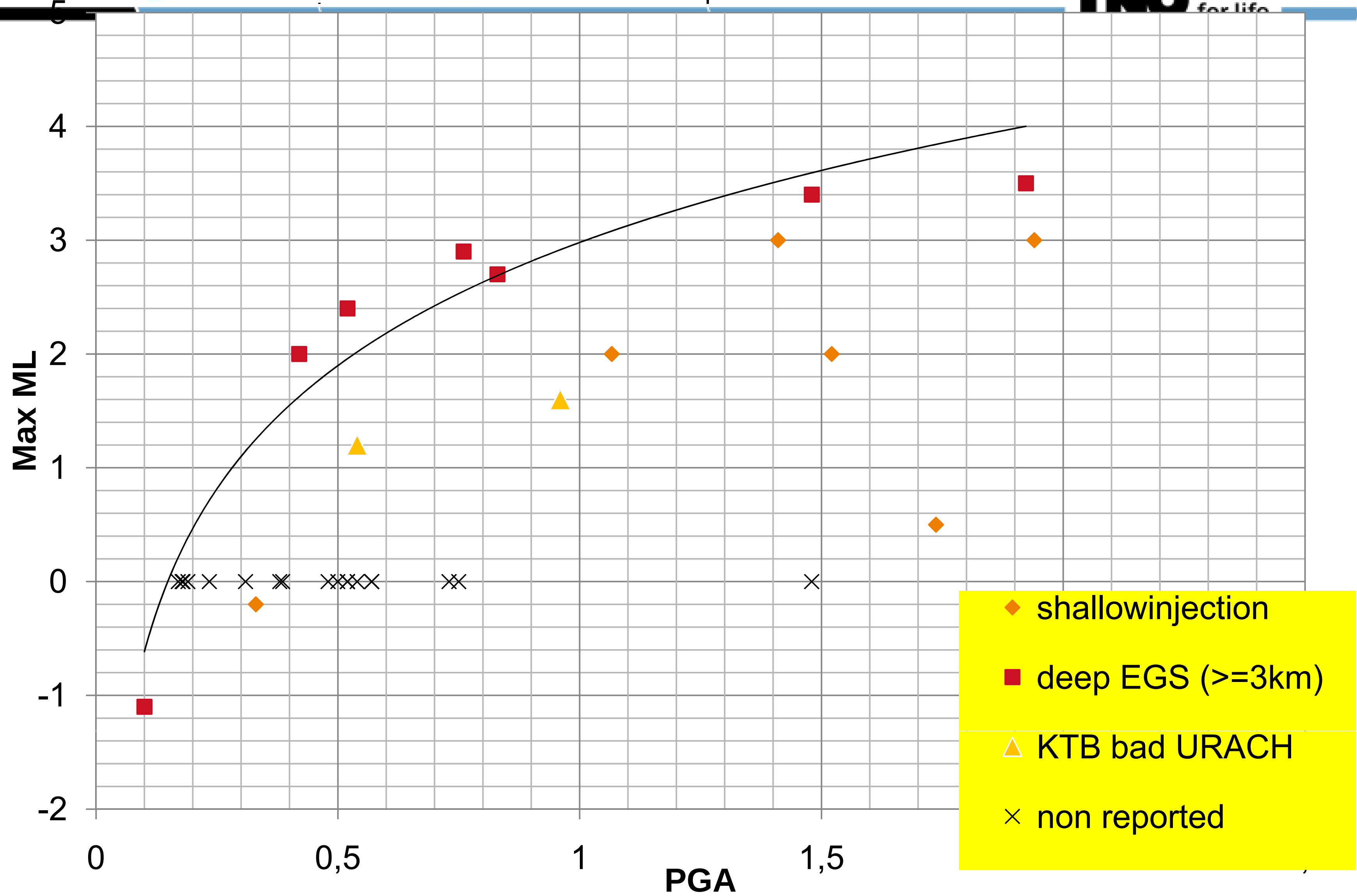


Evans et al., GJI, 2011





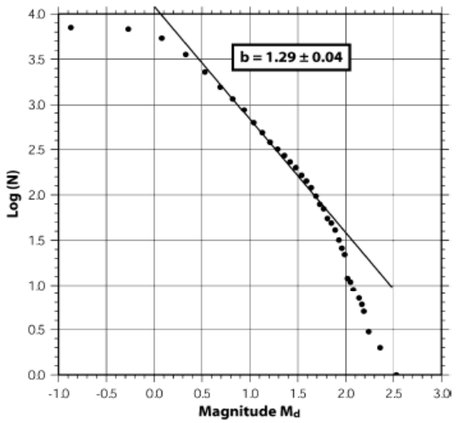
BRGM GFZ



Max ML
5
4
3
2
1
0
-1
-2
0
0,5
1
1,5
PGA
shallowinjection
deep EGS (>=3km)
KTB bad URACH
non reported

Desciptive models used in seismology

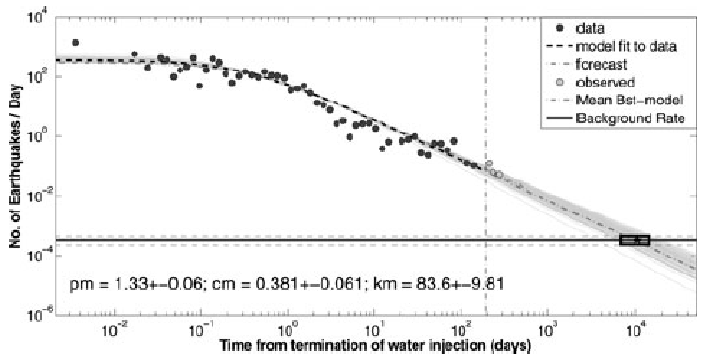
- **Gutenberg-Richter law**



$$\log N(m_i > m) = a - bm$$

- *b-value indicates the ratio of small to large events, a is a measure of the productivity*

- **Omori-Utsu law (for aftershocks)**



$$\lambda(t, M_c) = \frac{k(M_c)}{(t+c)^p}$$

t time since mainshock, c & p empirical parameters, $k(M_c)$ function of number of events with $M>M_c$

Both laws observed in EGS. They are used in statistical analysis

The Epidemic Type Aftershock Sequence (ETAS)

- **Each event triggers its own child-events** (Ogata, 1988).
- **Aftershock rate of an event → Omori-Utsu**
- **Number of aftershock related to M mainshock**
- **Aftershock distribution Gutenberg-Richter**

-Background seismicity λ0 + sum of rate of aftershock λi of an event with magnitude Mi at time t>ti (self-exciting point process)

-c and p parameters from the Omori-Utsu law

-K and α describe productivity of the sequence

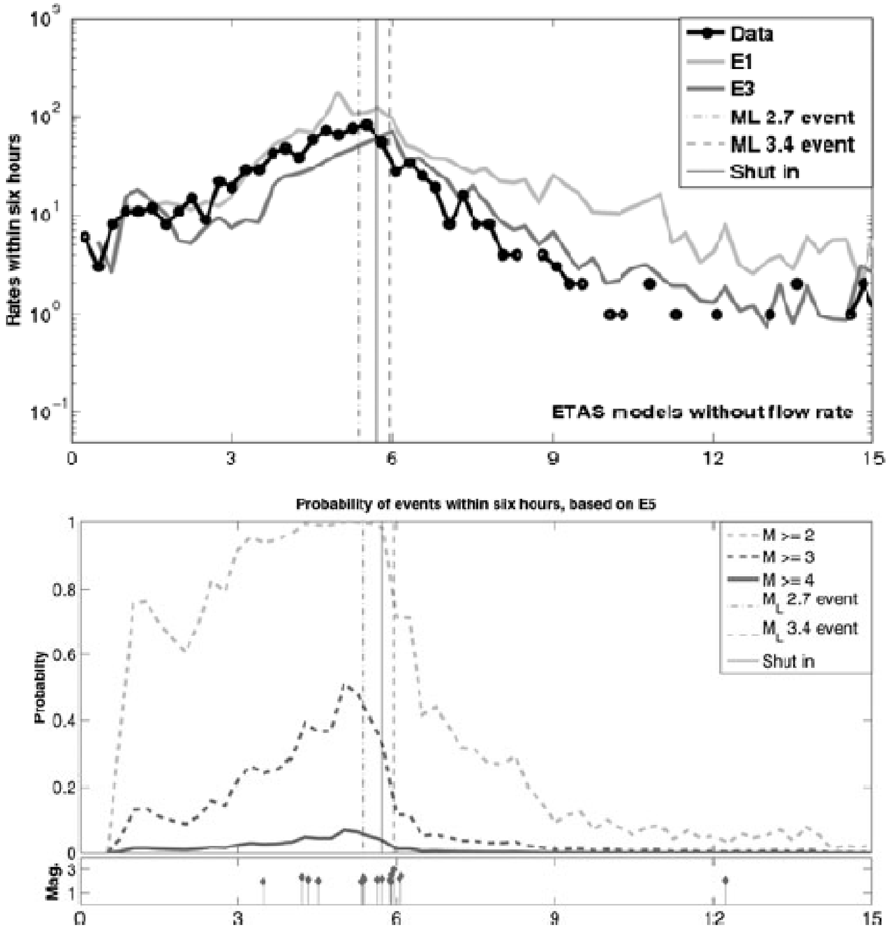
-Mmin magnitude of completeness or cutoff magnitude

$$\lambda(t) = \lambda_0 + \sum_{i:t<t_i} \lambda_i(t)$$

$$\lambda_i(t) = \frac{K}{(c+t-t_i)^p} 10^{\alpha(M_i - M_{\min})}$$

All parameters can be found by data fitting (maximum likelihood)

Application ETAS to EGS



Bachmann et al., 2011

- ETAS model to simulate observed seismicity rates in the December 2006 injection experiment in Basel (pseudo-prospective)
- Each 6 hrs parameters are updated to give 'real-time' forecast for the next 6 hr
- Seismicity rate of M_w = 0.9-3.5 is modeled

Statistical models: alternative to physics-based?

Bachmann et al. (2011)

- Well understood and well tested
- Catalogue input data available near real-time
- Relatively simple model to explain complex physical phenomenon
- Output seismicity rate → hazard estimates

- But no physical basis

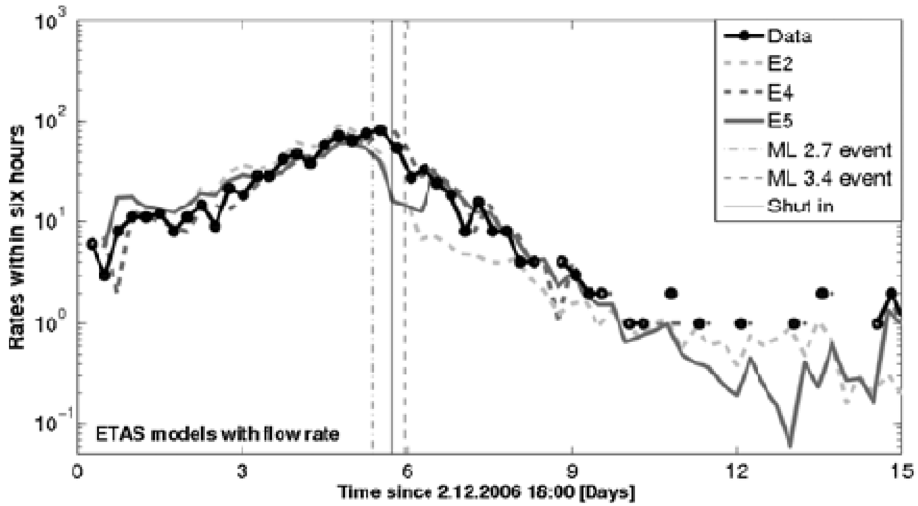
Integrated models: Including injection rate in ETAS

- Bachmann et al. (2011)

$$\lambda(t) = \lambda_0 + \sum_{i:t<t_i} \lambda_i(t)$$

$$\lambda_i(t) = \frac{K}{(c+t-t_i)^p} 10^{\alpha(M_i - M_{\min})}$$

$$\lambda_0(t) = \mu + c_f F_r(t)$$



Bachmann et al., 2011

Background is modified to include injection rate

- Better fit than models without injection rate

Seismogenic index

- Shapiro et al. (2010) **number of events proportional to injection volume**

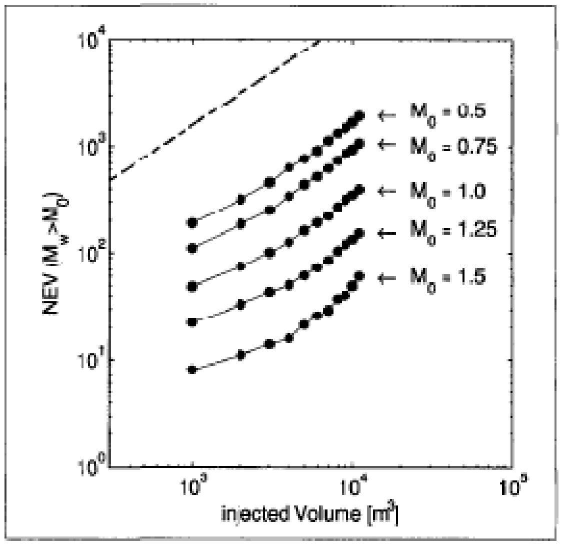
  Probability Shapiro et al. (2007) is rewritten as

$$\log N_M(t) = \log Qc(t) - bM + a - \log(F_t S)$$

- *Qc(t) cumulative injected volume*
- *S: poroelastic storage coefficient*
- *Ft concentration pre-existing cracks*

Seismogenix index:

$$\Sigma = a - \log(F_t S)$$



Shapiro et al., 2010

independent of injection parameters, **indicative of tectonic state at a specific site** (larger Σ = larger probability of significant magnitude events)

Probability of large events at Basel

- Basel → high seismogenic index

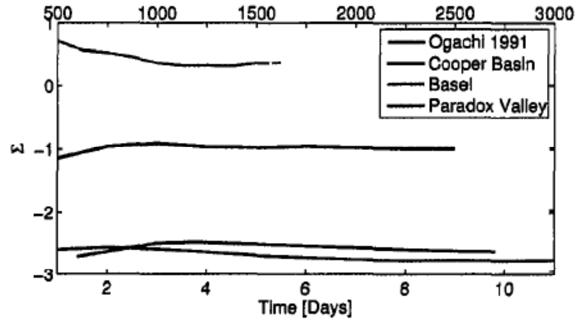
Poisson distribution → probability event with magnitude >M in time interval (0,t):

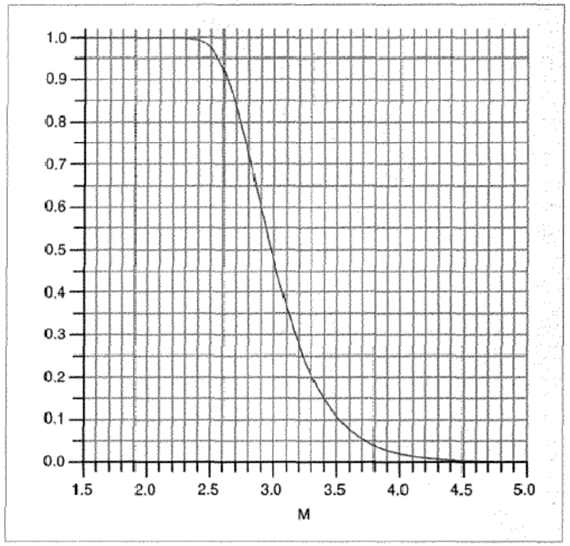
$$P(0, M, t) = \exp(-N_M(t))$$
$$= \exp(-Qc(t)10^{\Sigma - bM})$$

eg. for Basel 97% chance on M>2.5 during injection period

Post-injection seismicity?

Earthquake triggering?





Shapiro et al., 2010

Stress changes to seismicity rates

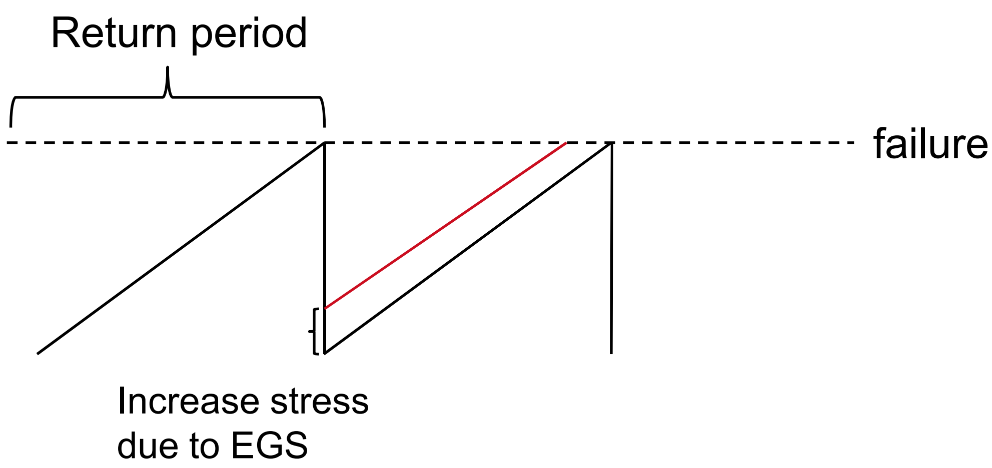
- Coulomb stress change, changes in normal stress, shear stress and pore fluid pressure

- Dieterich 1994 Rate-and-state friction based model
- Stress changes can be translated to seismicity rates

- But difficult model, many input parameters uncertain
  - Tectonic stressing rate
  - Background seismicity
  - Constitutive parameters

Maximum magnitude

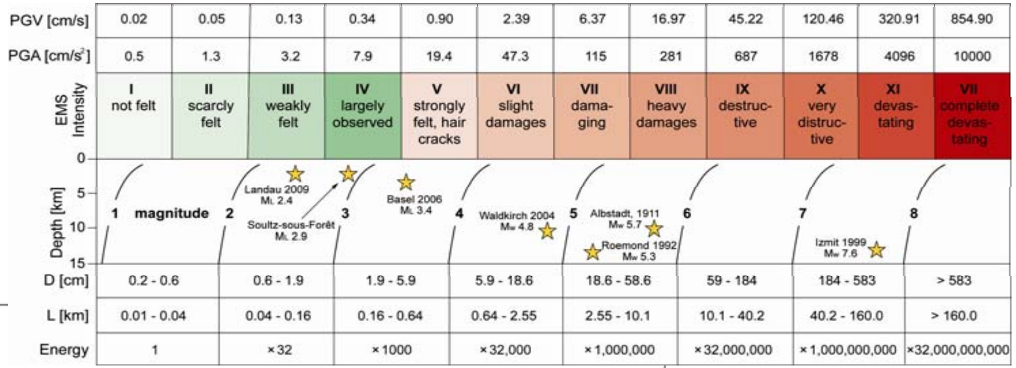
- Tectonic events: always large Mmax (Ml=6-7) over large return period
- EGS => decrease in return period large event



GEOELEC Supported by INTELLIGENT ENERGY EUROPE

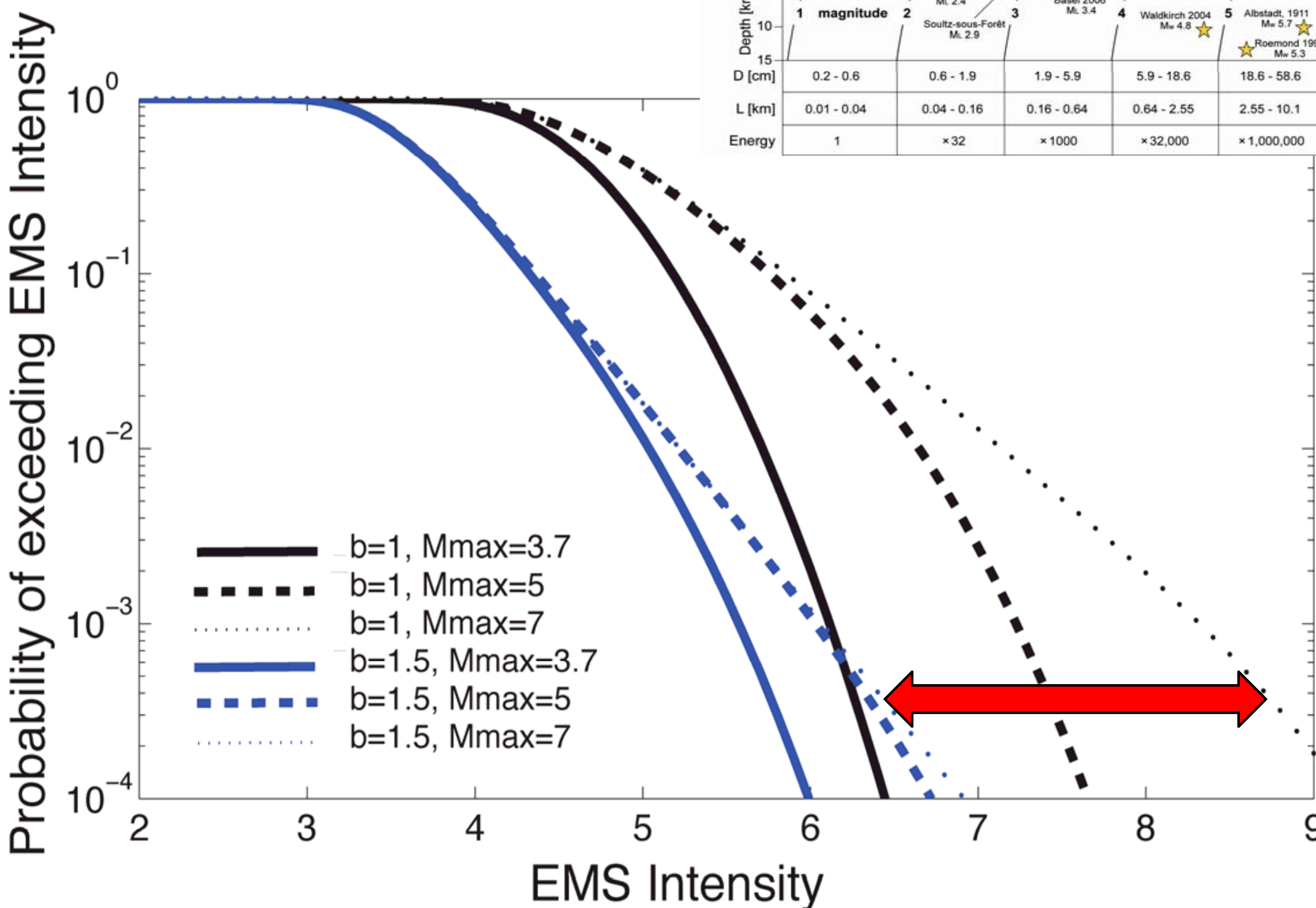
BRGM GFZ TNO innovation for life

Using Mmax and recurrance rate



PGV [cm/s]	0.02	0.05	0.13	0.34	0.90	2.39	6.37	16.97	45.22	120.46	320.91	854.90
PGA [cm/s²]	0.5	1.3	3.2	7.9	19.4	47.3	115	281	687	1678	4096	10000
EMS Intensity	I not felt	II scarcly felt	III weakly felt	IV largely observed	V strongly felt, hair cracks	VI slight damages	VII dama-ging	VIII heavy damages	IX destruc-tive	X very distruc-tive	XI devas-tating	VII complete devas-tating

magnitude	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8
D [cm]	0.2 - 0.6	0.6 - 1.9	1.9 - 5.9	5.9 - 18.6	18.6 - 58.6	59 - 184	184 - 583	> 583
L [km]	0.01 - 0.04	0.04 - 0.16	0.16 - 0.64	0.64 - 2.55	2.55 - 10.1	10.1 - 40.2	40.2 - 160.0	> 160.0
Energy	1	×32	×1000	×32,000	×1,000,000	×32,000,000	×1,000,000,000	×32,000,000,000



Bachmann et al., 2011

The in-depth physics based view

WHITE PAPER on physical processes and key parameters

Authors

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J-D. van Wees, P. Fokker (TNO)

A. Zang, O. Heidbach (GFZ)

Title

"Induced seismicity in geothermal reservoirs:

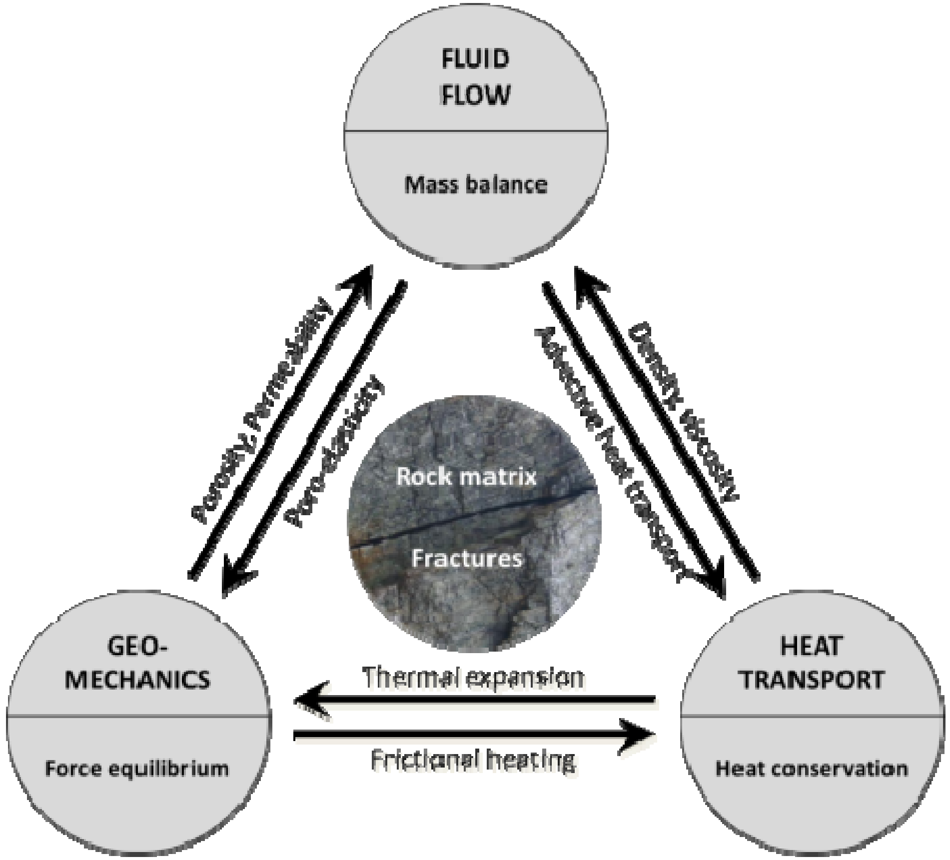
physical processes and key parameters"

Outline

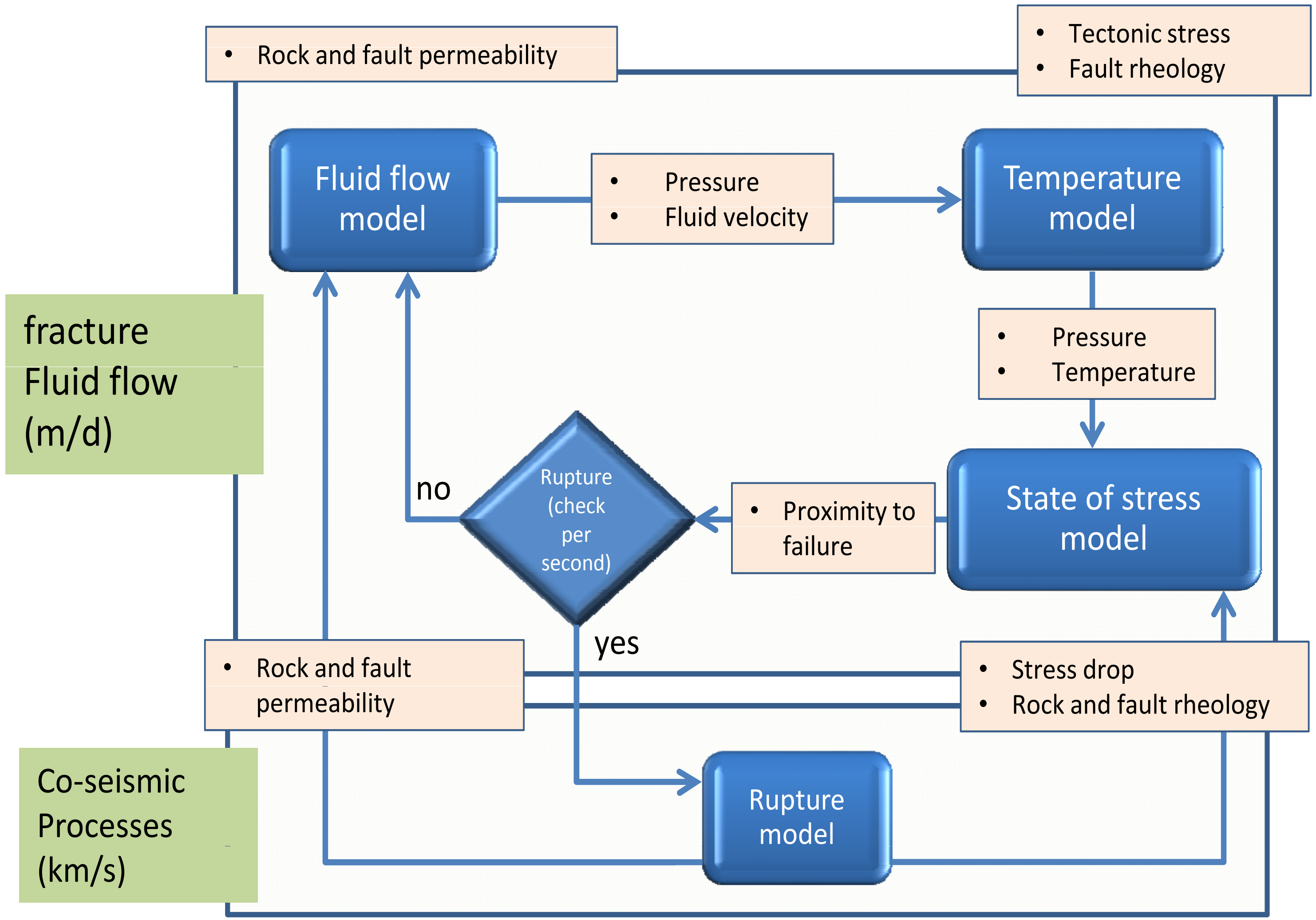
- Context and scientific background
- Models related to seismicity observation
- Physics-based models of induced seismicity process (M. Schoenball)
- Case studies: Soultz-sous-Forêts & Gross-Schoenebeck
- Key parameters and way forward

Coupled processes

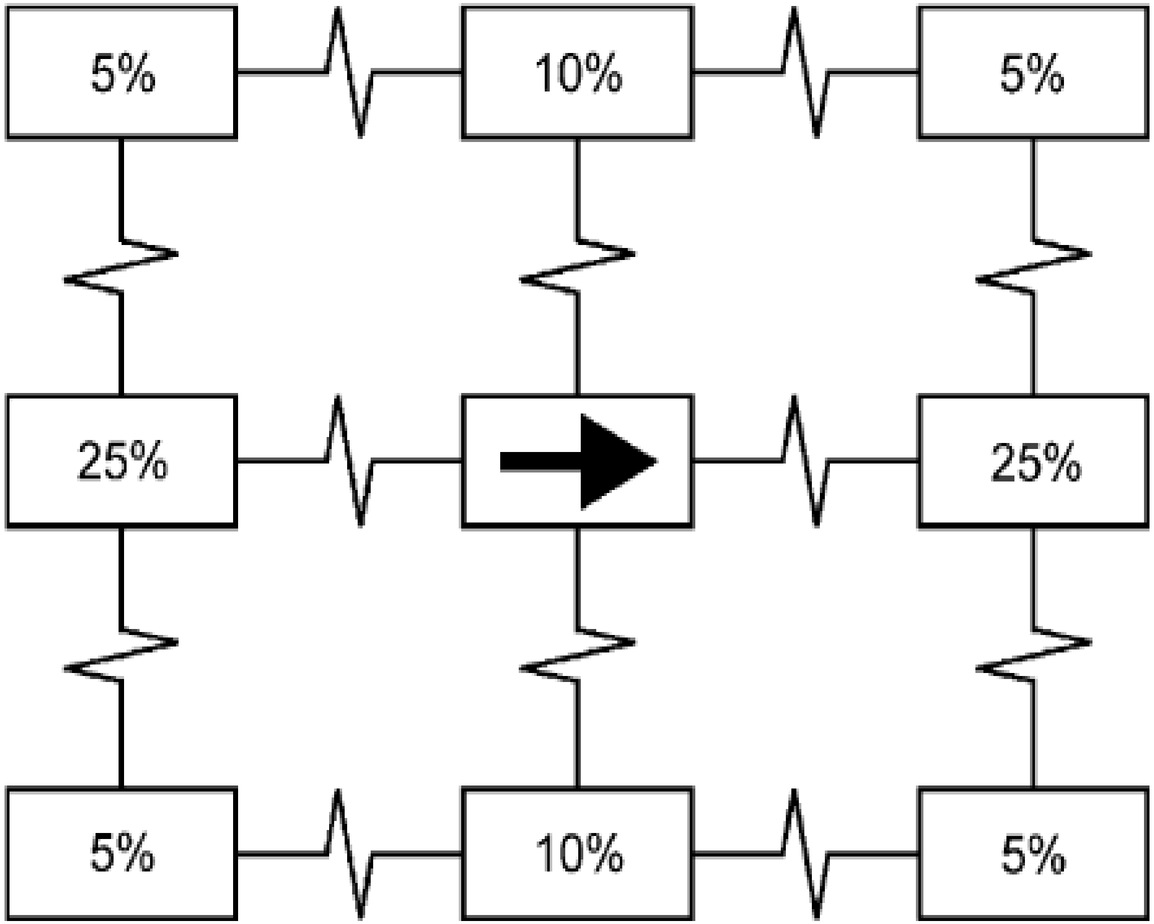
- IS in geothermal reservoirs results from interaction of
  - Fluid flow
  - Heat transport
  - Geomechanics
- Deterministic models have been developed to answer part of these interactions



Physical models



Very Simplified Rupture model (Baisch et al., 2010)



Rupture model
(Baisch et al., 2010)

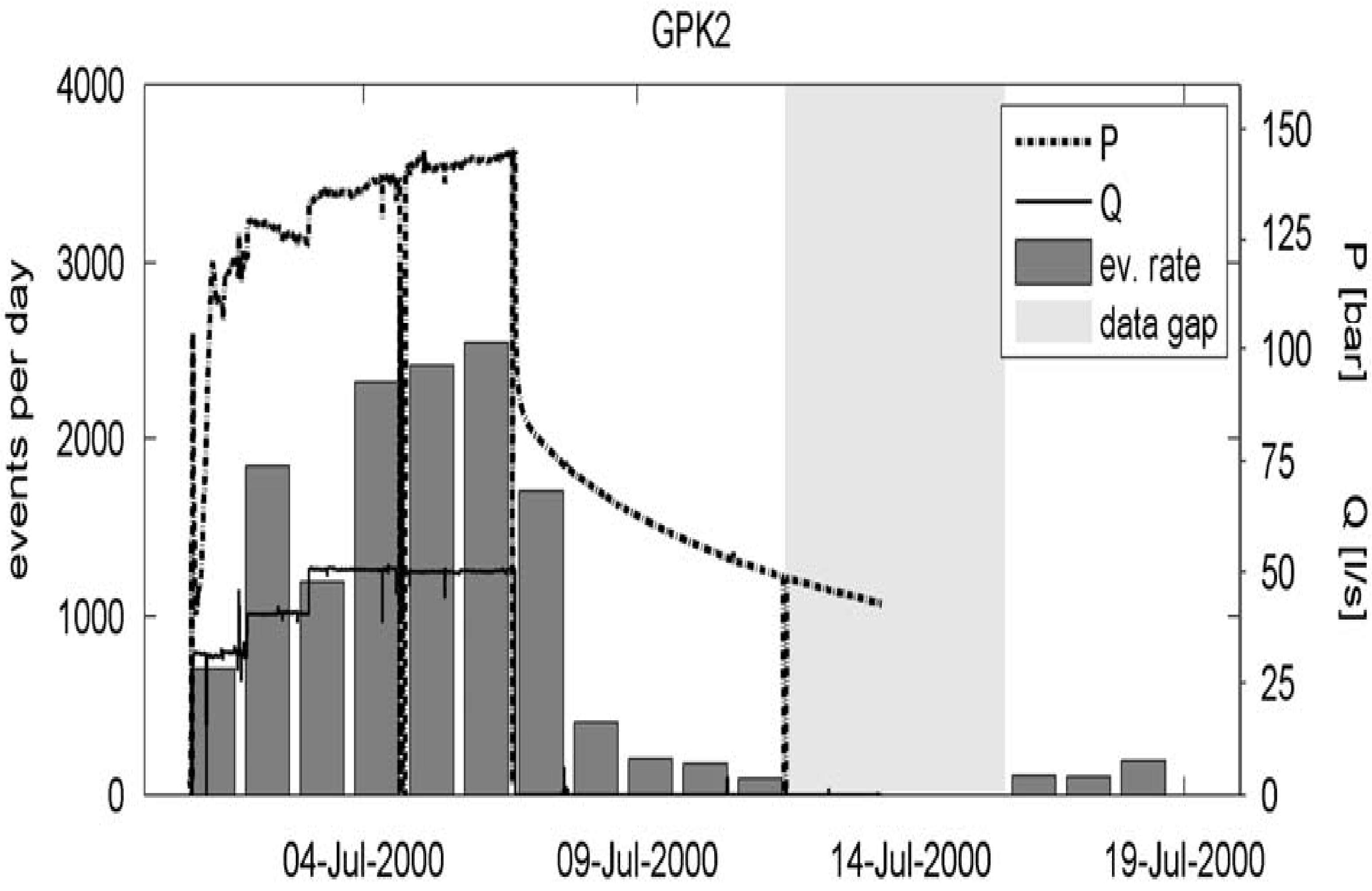
Stressdrop transfer to Neighbouring patches

Stressdrop can trigger other pathes → avalanche

Stress drop 3-30bar

Stress drop related to shearstrain→ opening of fracture→ 10-20% increase of transmissivity

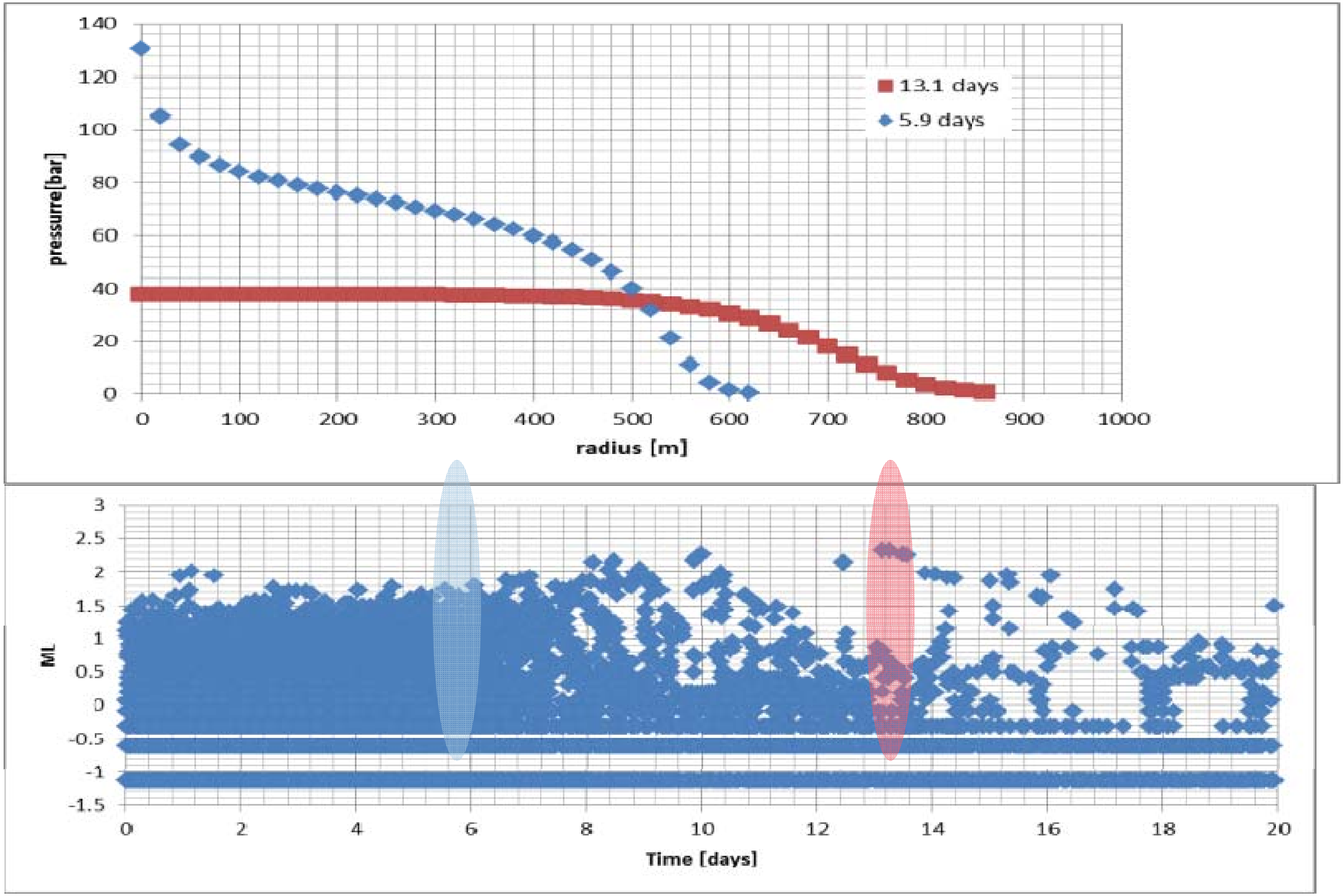
Soultz


GPK2
4000
3000
2000
1000
0
events per day
150
125
100
75
50
25
0
P [bar]
Q [l/s]
P
Q
ev. rate
data gap
04-Jul-2000
09-Jul-2000
14-Jul-2000
19-Jul-2000

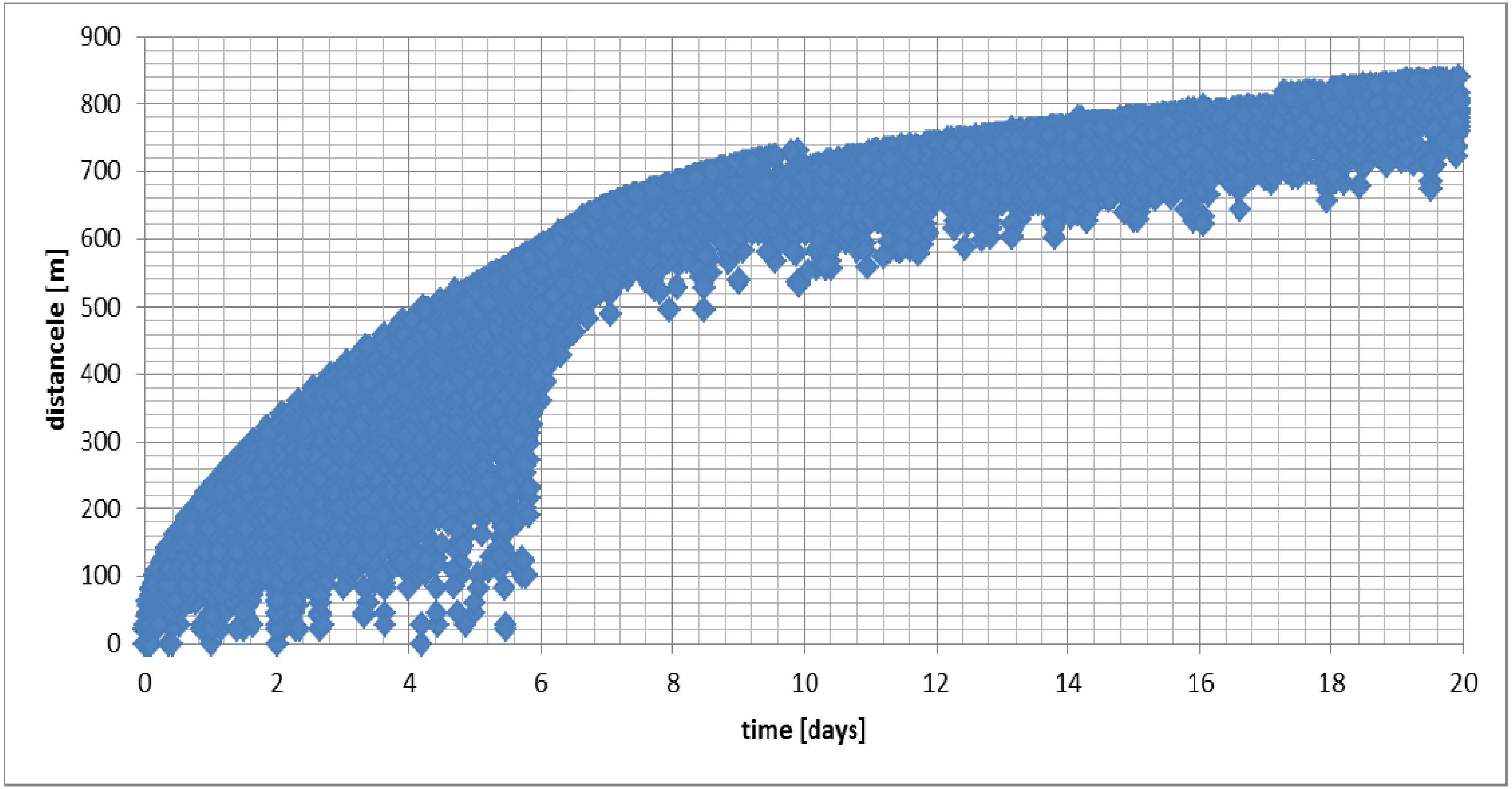
parameters

Parameter	Symbol	Value	Units
Initial transmissibility	T	10	mDm
Storage coefficient	S	5e–9	m/Pa
Dyn. viscosity	μ	2.4e–4	Pa s
Width	h	1	mm
Well radius	rw	0.1	m
Stress drop	$\Delta\tau$	1	MPa
Sampling interval	Δt	1	s

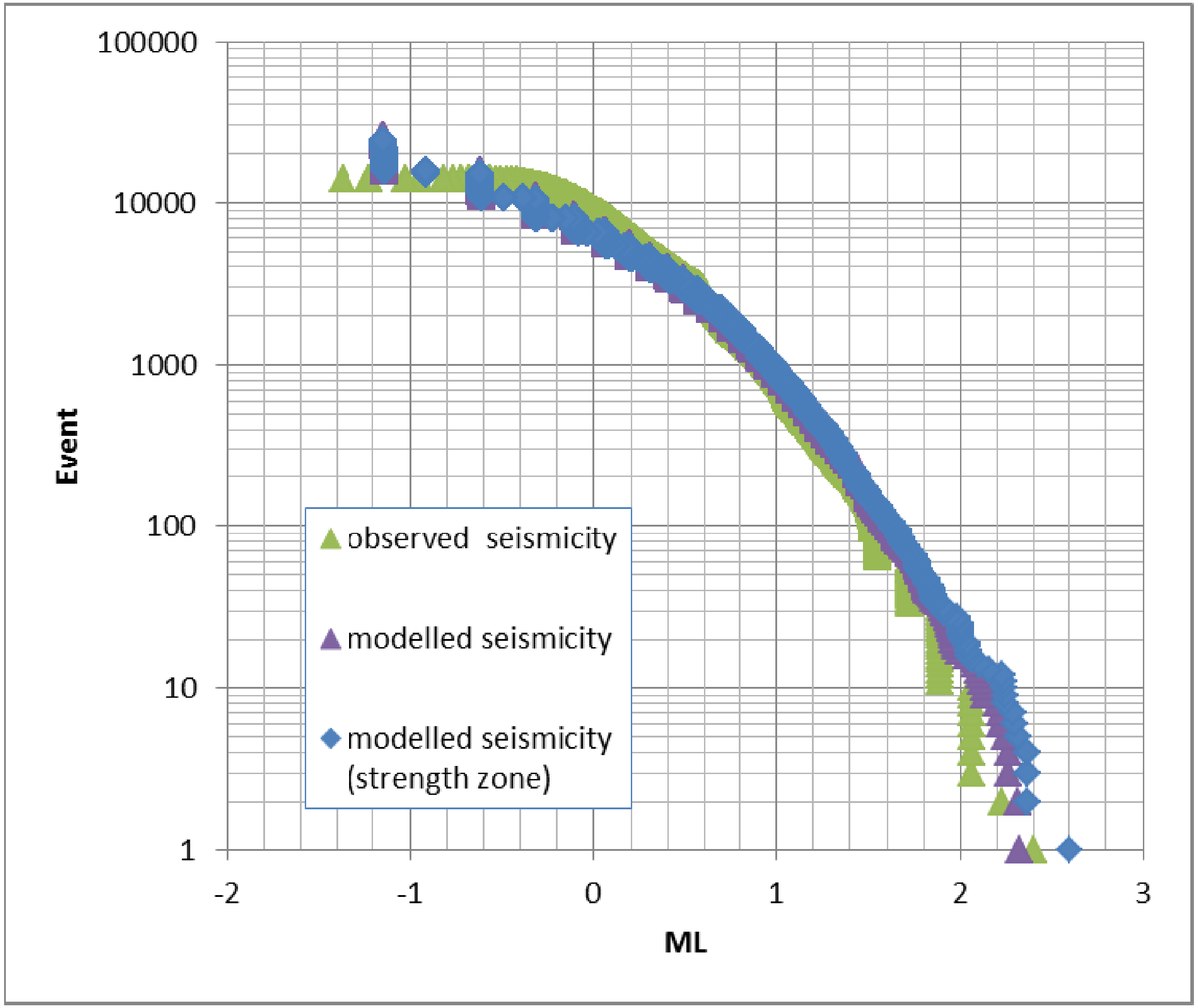
Largest events post shut-in → lower



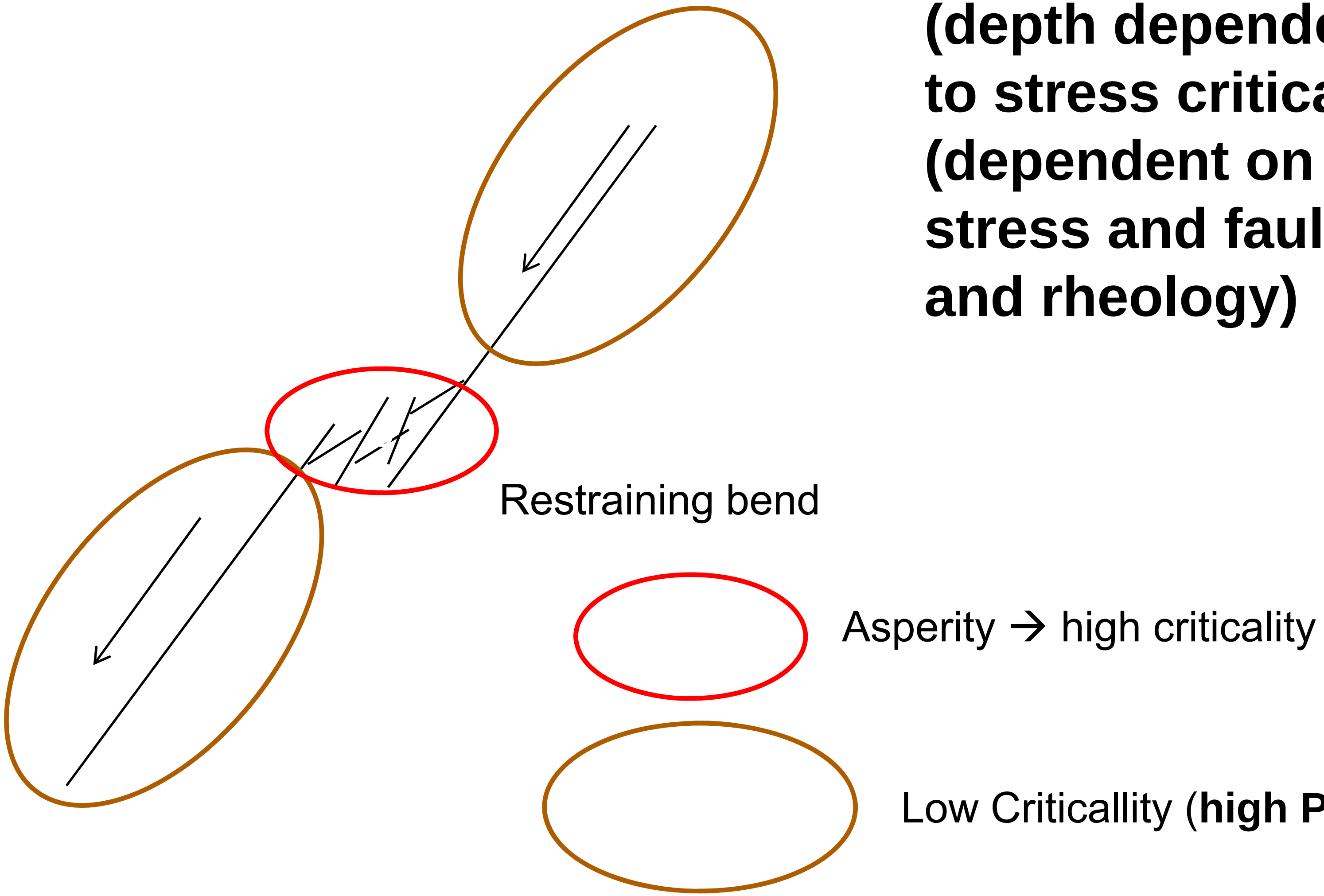
Kaiser effect



Strength zone with large stress drop- not realistic

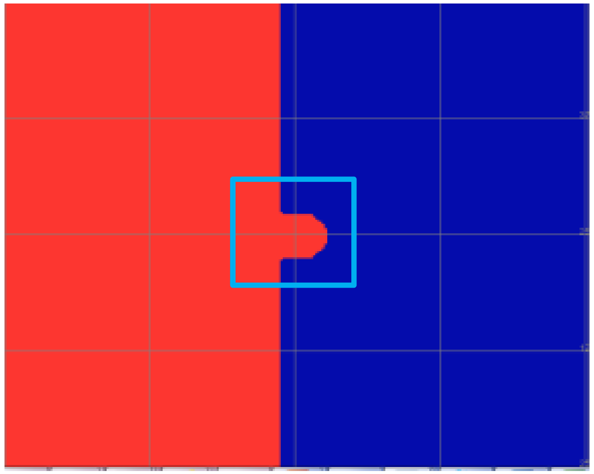


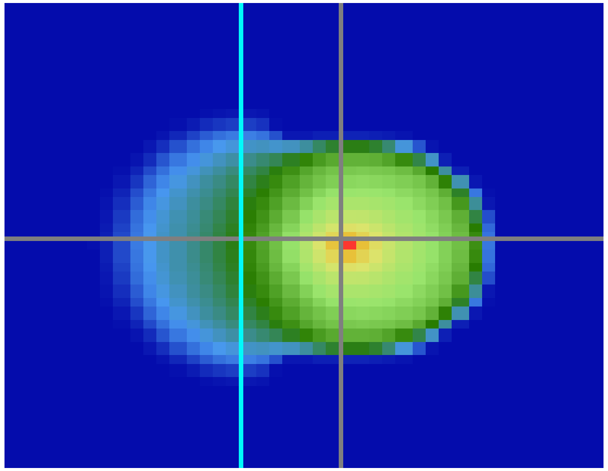
Heterogenity in **stress drop (depth dependent) relative to stress criticallity (dependent on natural stress and fault geometry and rheology)**



Larger stress drop than proximity to failure (Baisch et al., 2010) model

pressure





Low criticality high criticality

Stress drop ==
1 Mpa

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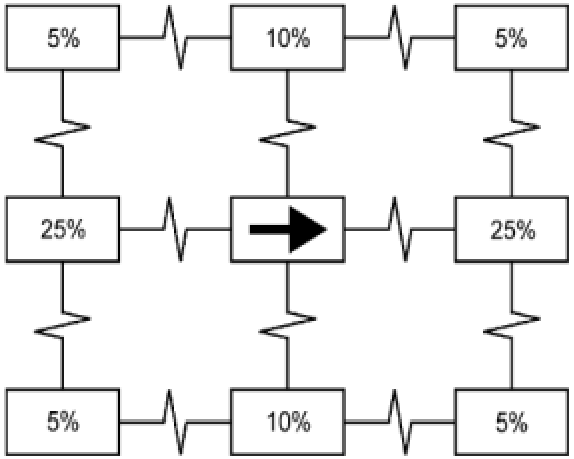
Improvements baisch and voros model

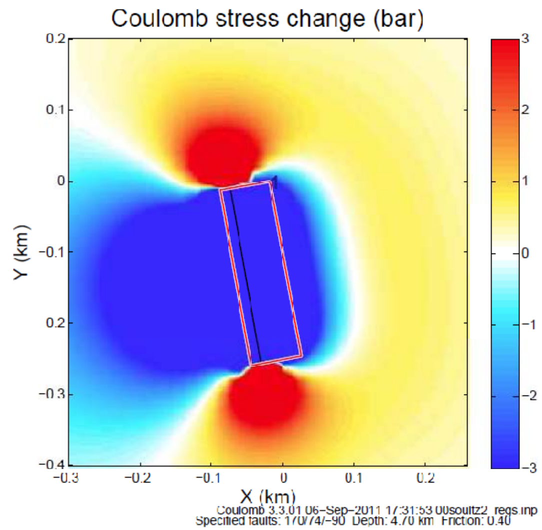
› Limitations:

- Kernel limits stress transfer to next patch only
- Large stress drops cannot be transferred over larger distance
- Strong lateral attenuation



Improvements:

- Full stress transfer kernel required
- Adopt okada kernel of BEM
- Instead of stressdrop use static and dynamic friction (rate and state)



Progress in THM modelling in +/- continuous media

> **Coupled modeling of fracture reactivation in EGS reservoir (TNO)**

➔ Development of a new tool for modelling the coupled response and reactivation of pre-existing fracture (FLAC3D, extended with fracture code [reactivation, no creation])

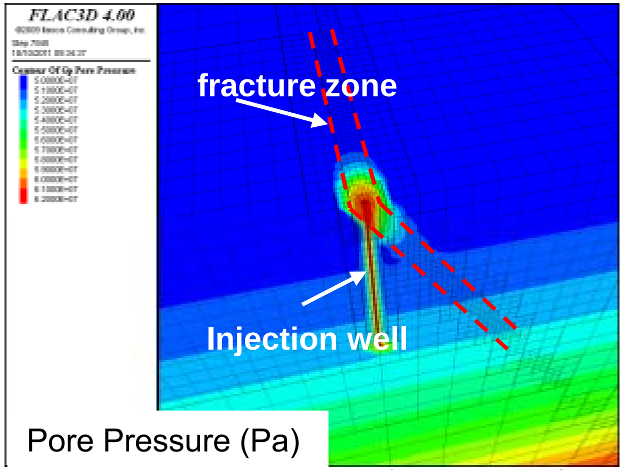
➔ Focus on:

➔ reactivation of natural fracture network in low permeability rock

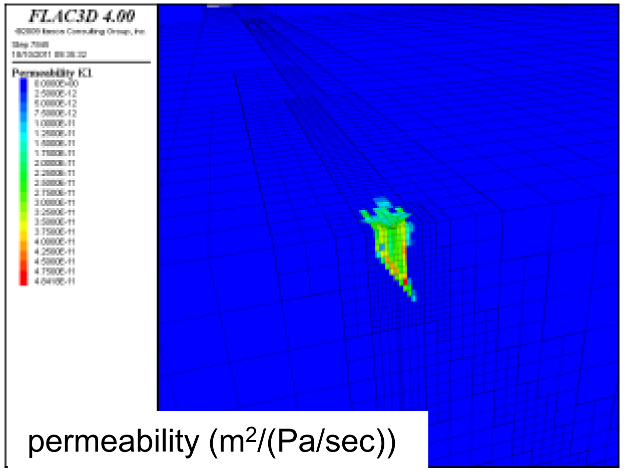
➔ role of pore pressures & temperatures in relation to permeability enhancement and seismicity

➔ Application: Soultz-sous-Forêts

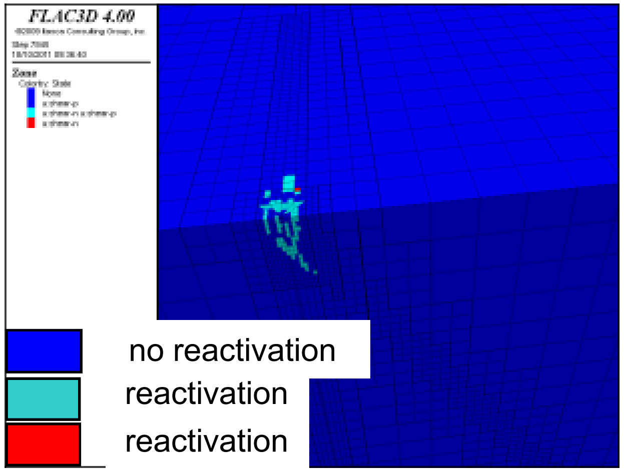
Reactivation of fault zone



(from Wassing et al., TNO, 2011



(from Wassing et al., TNO, 2011



(from Wassing et al., TNO, 2011

pore pressures in fracture zone 7.5 hours after start injection	permeability increase in fracture zone 7.5 hours after start injection	reactivated fractures in fracture zone 7.5 hours after start injection

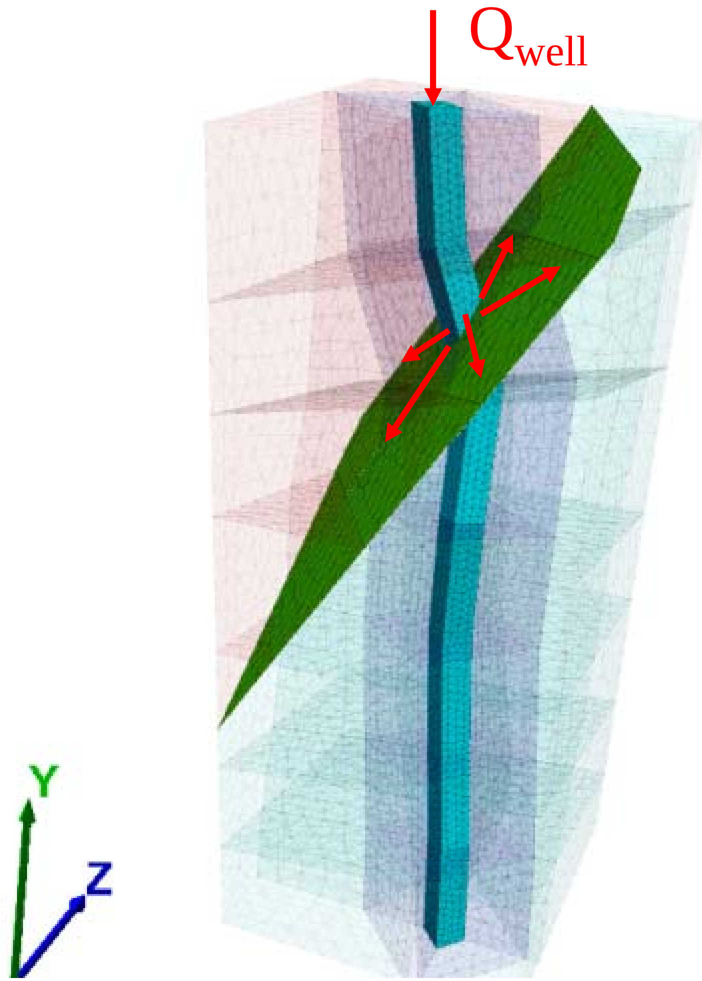
- **Tool** will help investigating the relations between injection rates, permeability enhancement and fracture reactivation potential
- **Work planned:** Further code extension for modelling temperature effects

Progress in (T)HM modelling in fractured media

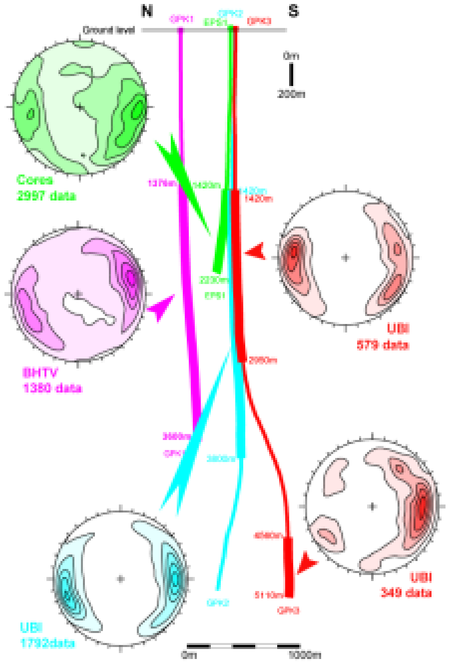
> **Study of fault segment 3D network during hydraulic stimulations (BRGM)**

➔ 3D DEM approach, with a specific (T)HM coupling

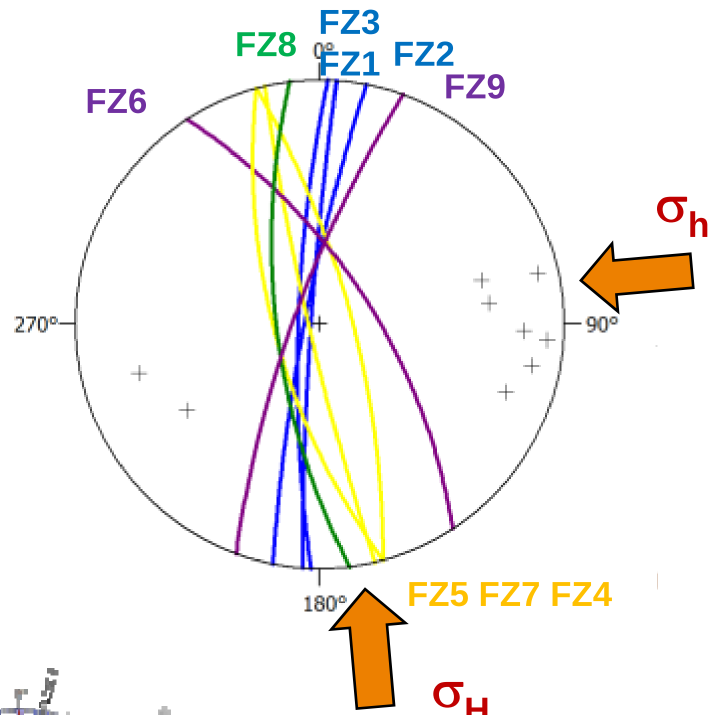
- ➔ Deformable and impermeable blocks
- ➔ Flow takes place only in fault zones
- ➔ HM coupling. Permeability increase due to associated dilation effect during sliding and/or due to opening of a fault zone due to stress redistribution
- ➔ THM coupling. Thermal convection by the fluid within the fractures. Thermal exchanges between the fluid and the rock mass. Ability to account for thermal stresses



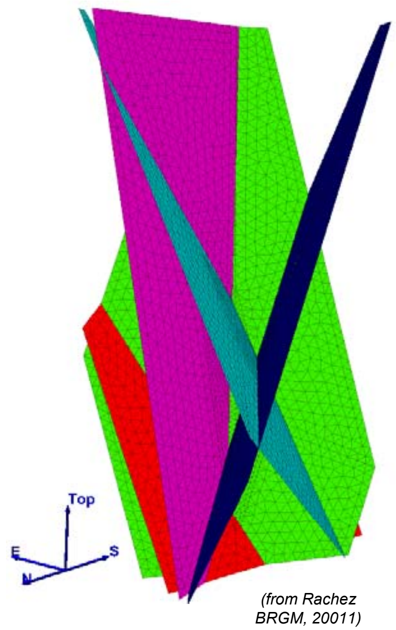
3D Fracture network geometry ⇔ Modeling



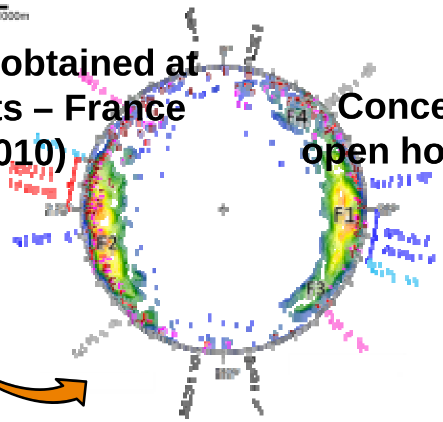
Row 1D well data obtained at Soultz-sous-Forêts – France (From Dezayes, 2010)



Conceptual model for GPK4 open hole at Soultz-sous-Forêts



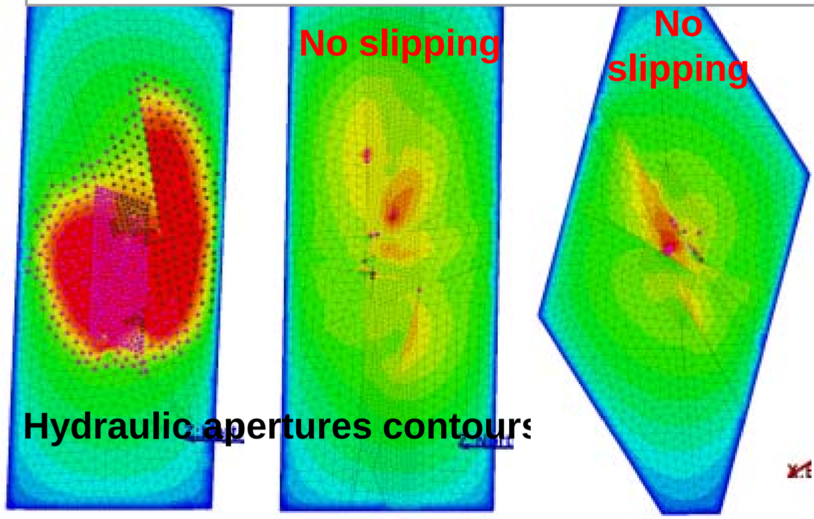
Numerical model (DEM)



Correction from well trajectories, etc. (Peter-Borie, 2011)

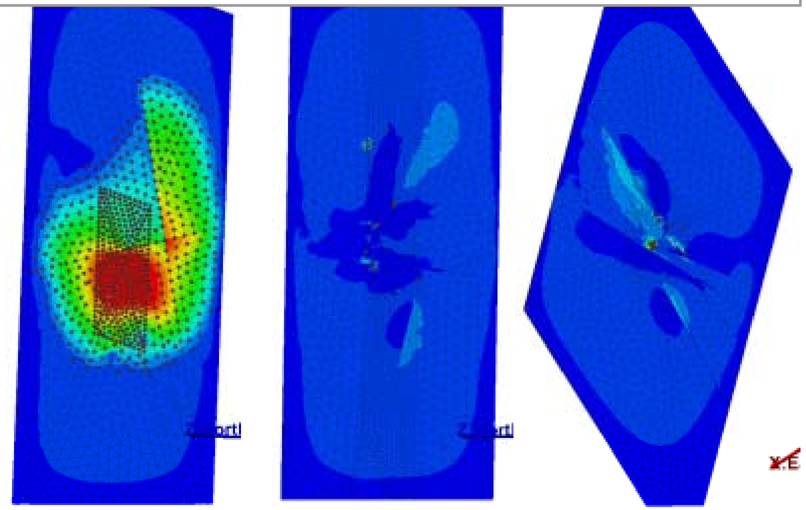
3D network - Different fault zones' behaviors

End of stimulation – ΔP=12.5MPa

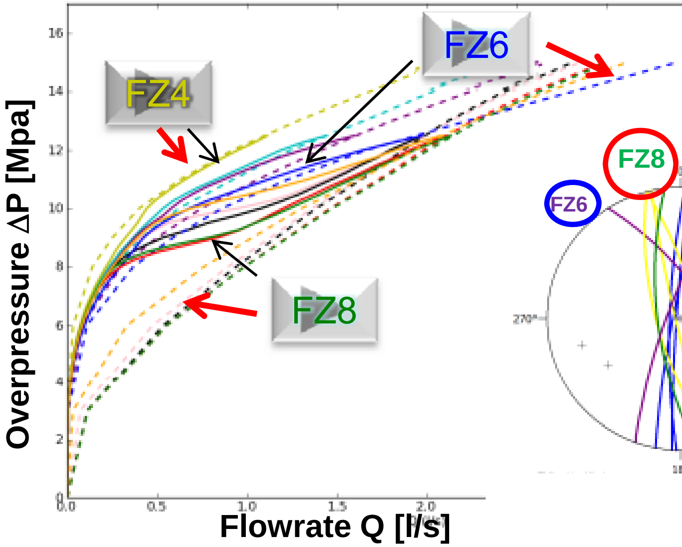


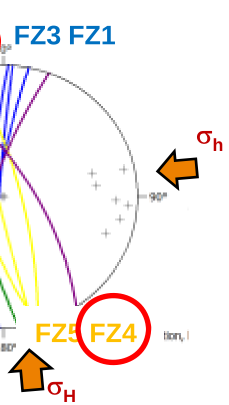
FZ8–N173°E FZ4–N167°E FZ6–N147°E

Well shut in – ΔP=0Mpa

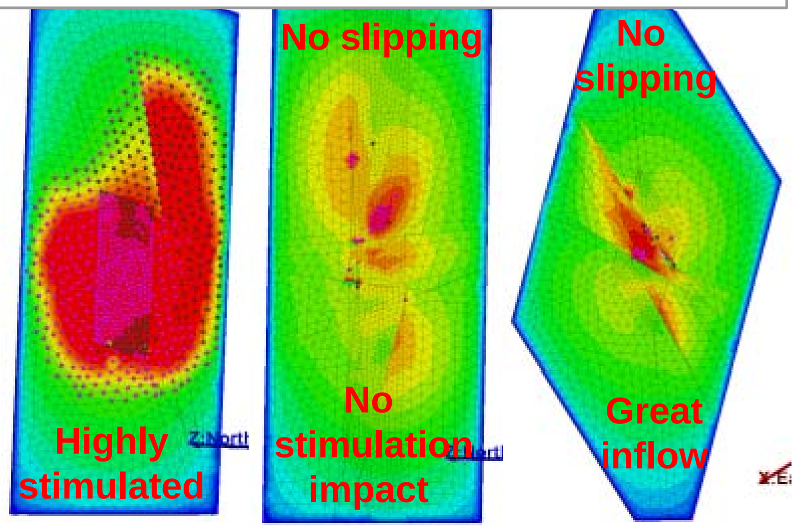


FZ8–N173°E FZ4–N167°E FZ6–N147°E

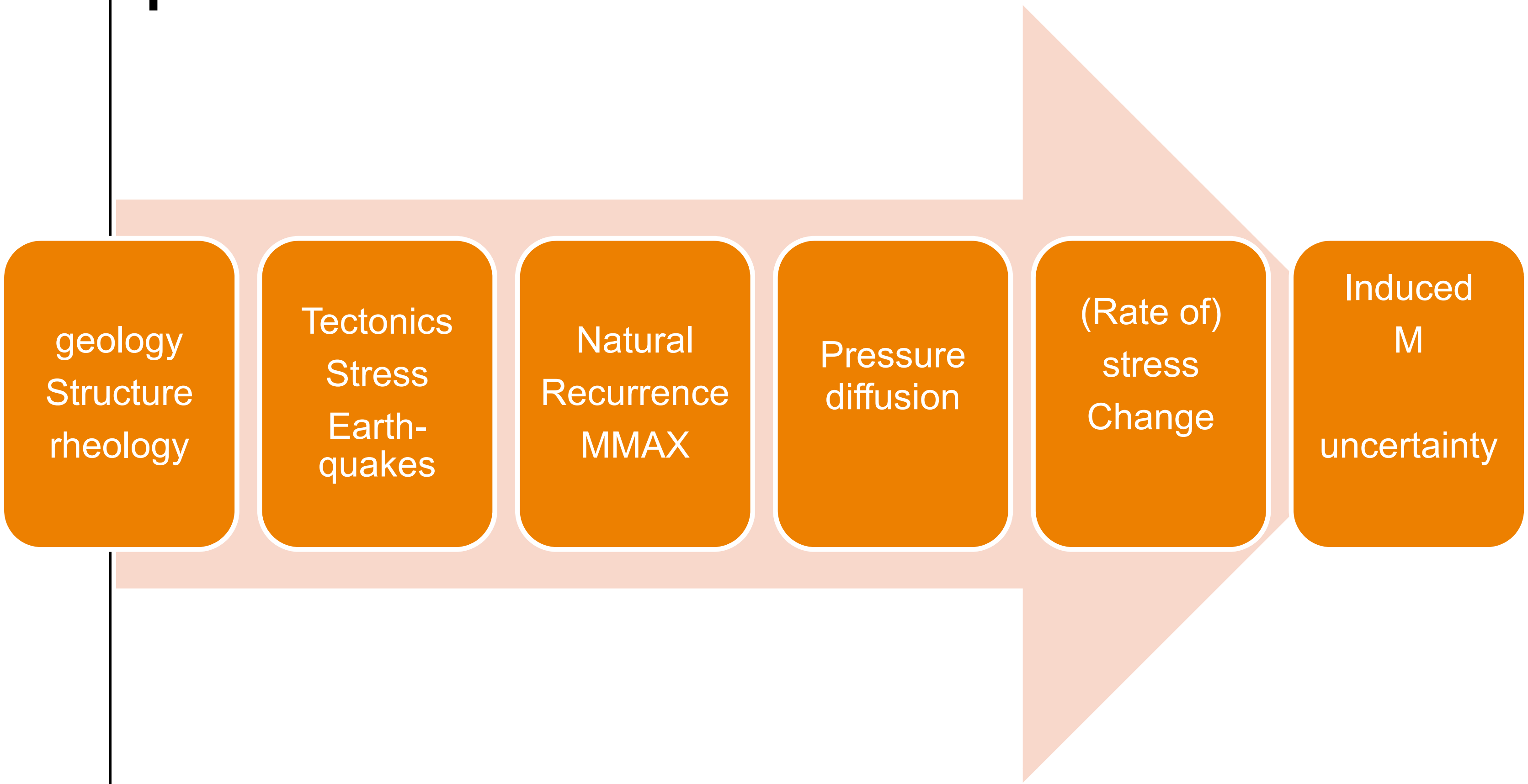




Post stimulation injection ΔP = 15.0MPa




Spatial differentiation in Parameters and processes

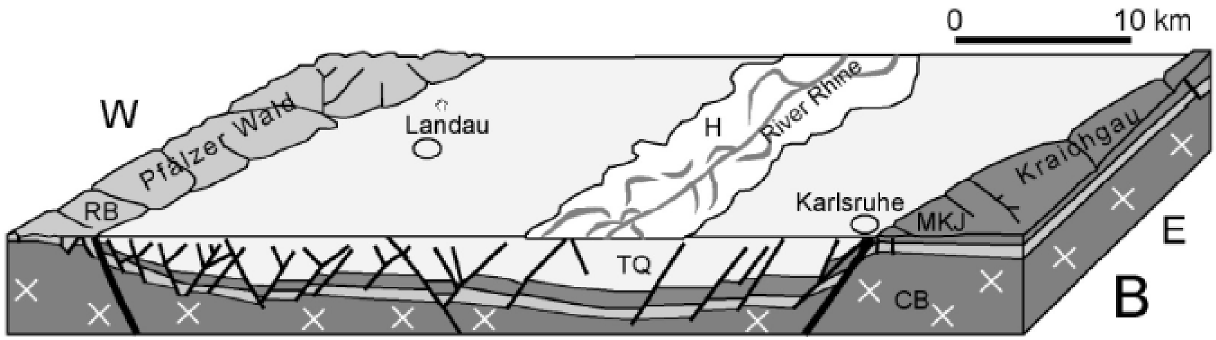


Mmax=7, 70x10 km fault, 1m displacement

Mmax=6, 30x5 km fault, 0.4m displacement

Mmax=5, 15x5 km fault, 0.15m displacemen

Big earth quakes
Located at
Mapped Major faults



→ stay away from seismically active faults

GEISER

T6.5 Provide boundary conditions for regulatory guidelines

(TNO, ETHZ, KNMI, INGV, ISOR)

Regulatory guidelines are needed both **prior to any operations**, when **licenses** need to be given, and **during operations, when seismicity may appear**. The **goal** is to provide **guidelines to help regulators** in devising **seismic hazard assessment specifications for the selection, licensing and long-term operation of EGS sites and for injection operations** in different geological settings. A clear distinction will be made between guidelines for exploration and drillling licensing, where decisions must be taken on the basis of a priori information when little is still known about the reservoir, and guidelines for operations, when measurements are building up the knowledge gradually.

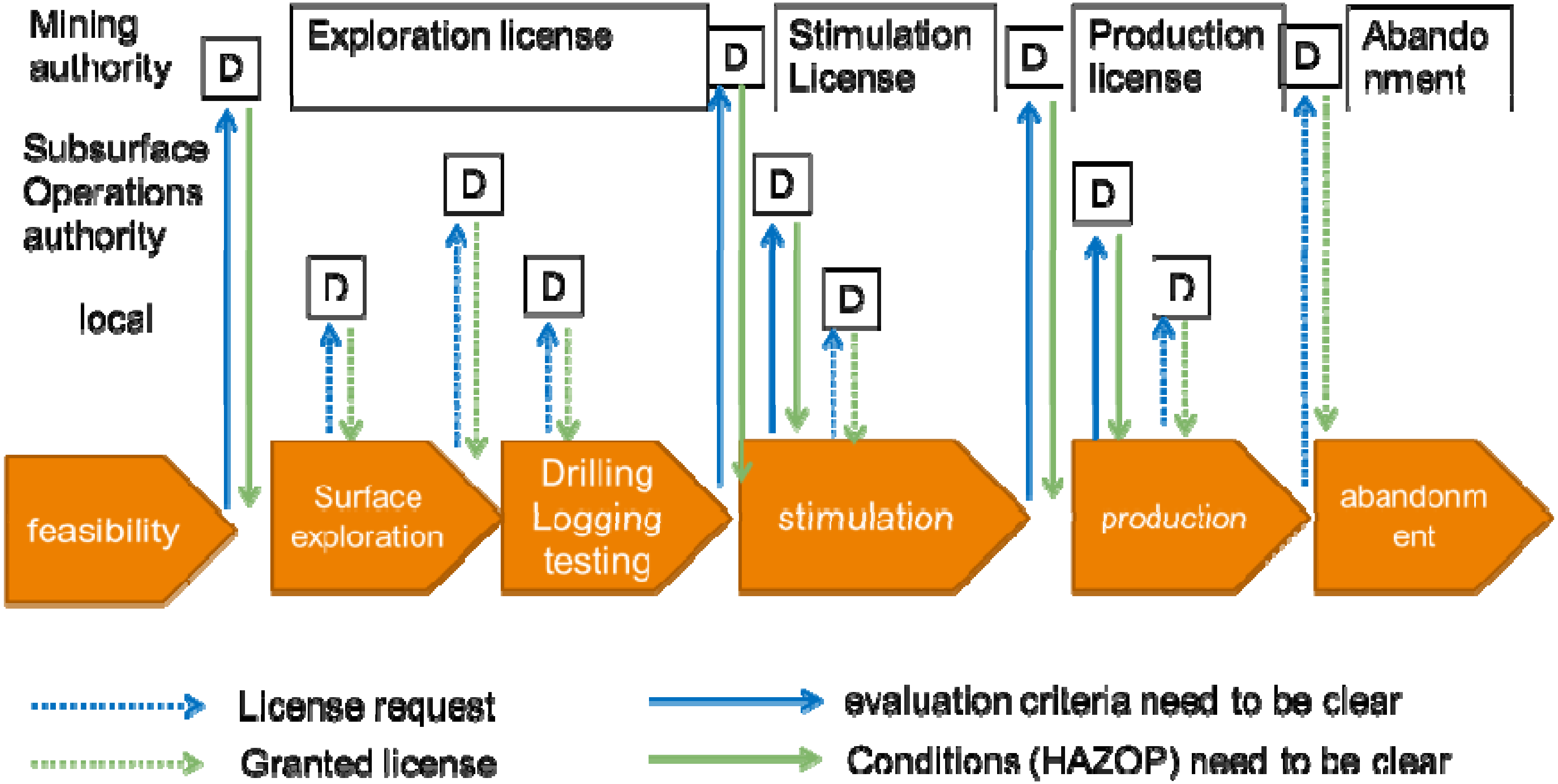
Task 6.5: key components to be connected in the regulatory guidelines for seismic hazard: a Dutch View

Regulations for licensing and operations
(exploration, drilling&stimulation, operations)

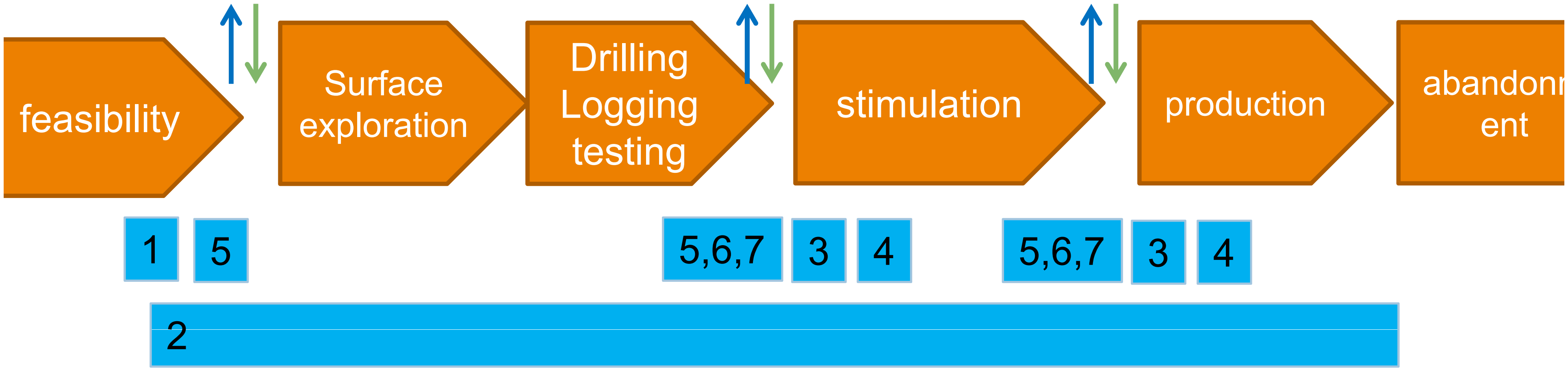
Best project practices (US) and technical state-of-the-art (GEISER)

flexibility and freedom to adapt to advancement in understanding in KEY processes (GEISER and beyond)
And leave technical details to project developers

Project Workflow orientation:regulatory decision tollgates



T 6.5: Provide boundary conditions for regulatory guidelines



Connect for conditions and criteria to US PROJECT BASED protocol (Maier et al., 2012)

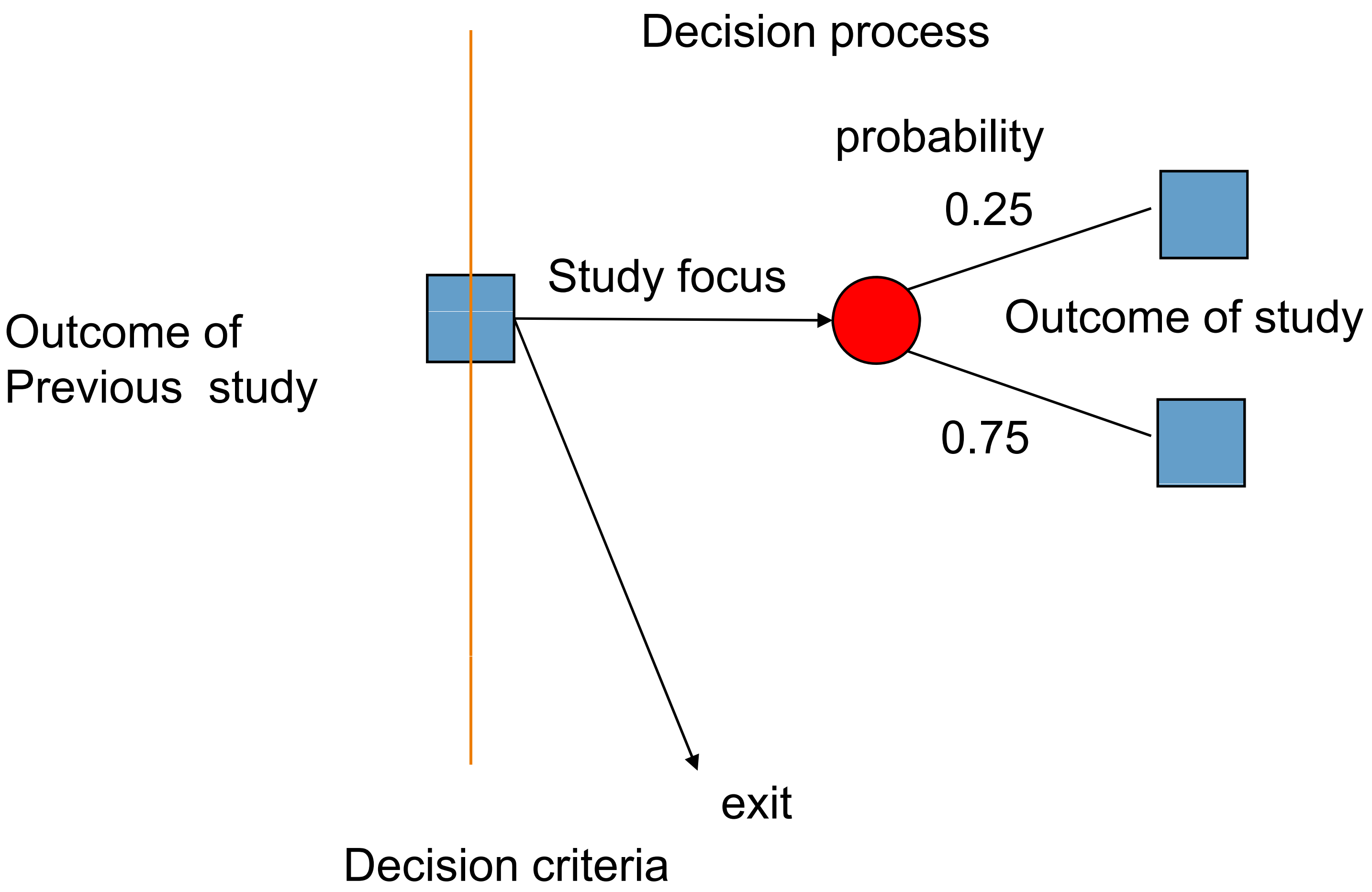
1) Perform a preliminary screening evaluation
2) Implement an outreach and communication program
3) Identify criteria for ground vibration and noise
4) Establish seismic monitoring
5) Quantify the hazard from natural and induced seismic events
6) Characterize the risk from induced seismic events
7) Develop risk-based mitigation plans

- What can we expect from GEISER and how can we use the US protocol
  - Licence criteria and conditions

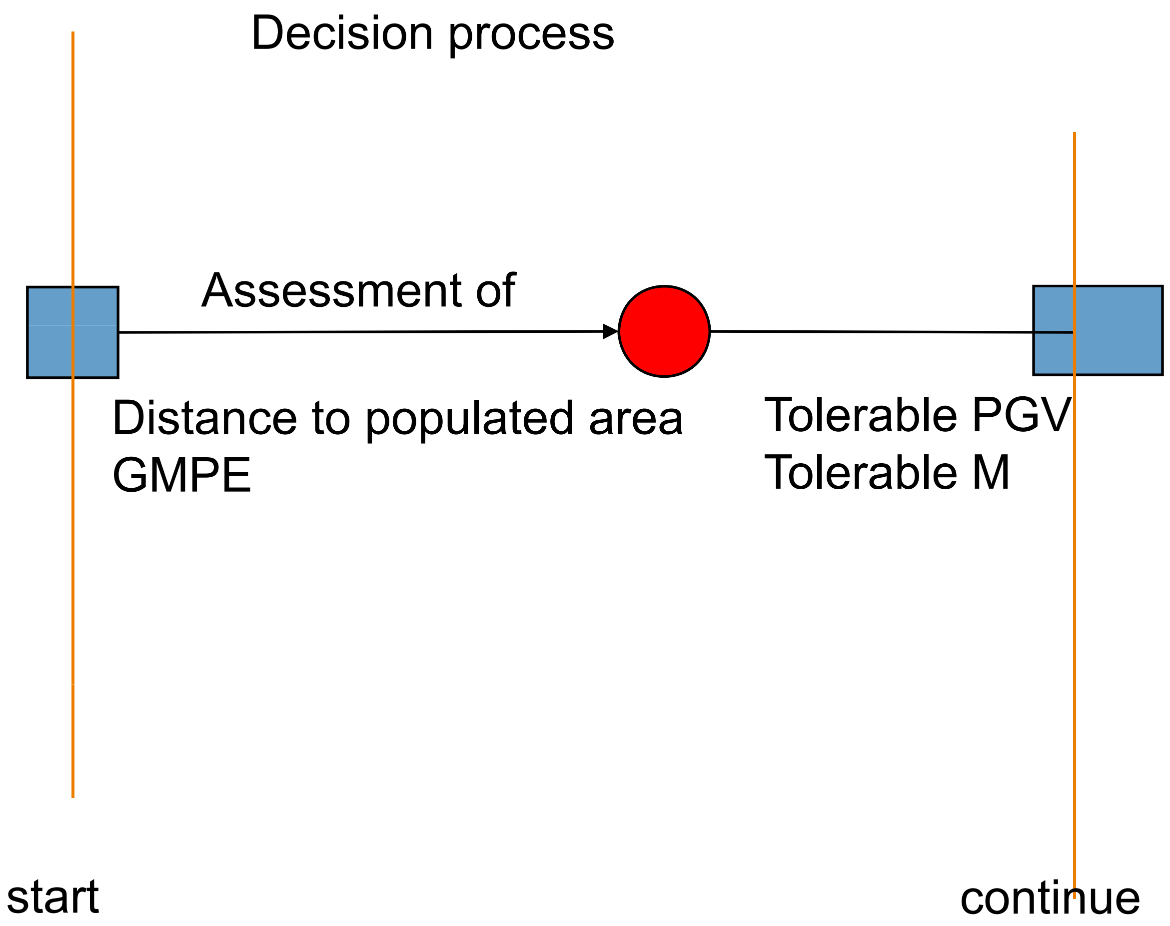
  - Technical recommendations for operations
    - **seismic hazard assessment** → *methodology and key parameters* for a priori site specific assessment → **expected level of seismicity in conjunction with impact, to be included in license requests**

    - Seismic monitoring and **Dynamic traffic light**
      - Dynamic because it includes a *prediction of seismicity based on key parameters and monitoring sofar*. Treshold ML to stop operations is related to predicted value, not observed ML (**US protocol recommends 0.9 difference**)
      - It allows for validation of a priori assumption during stimulation

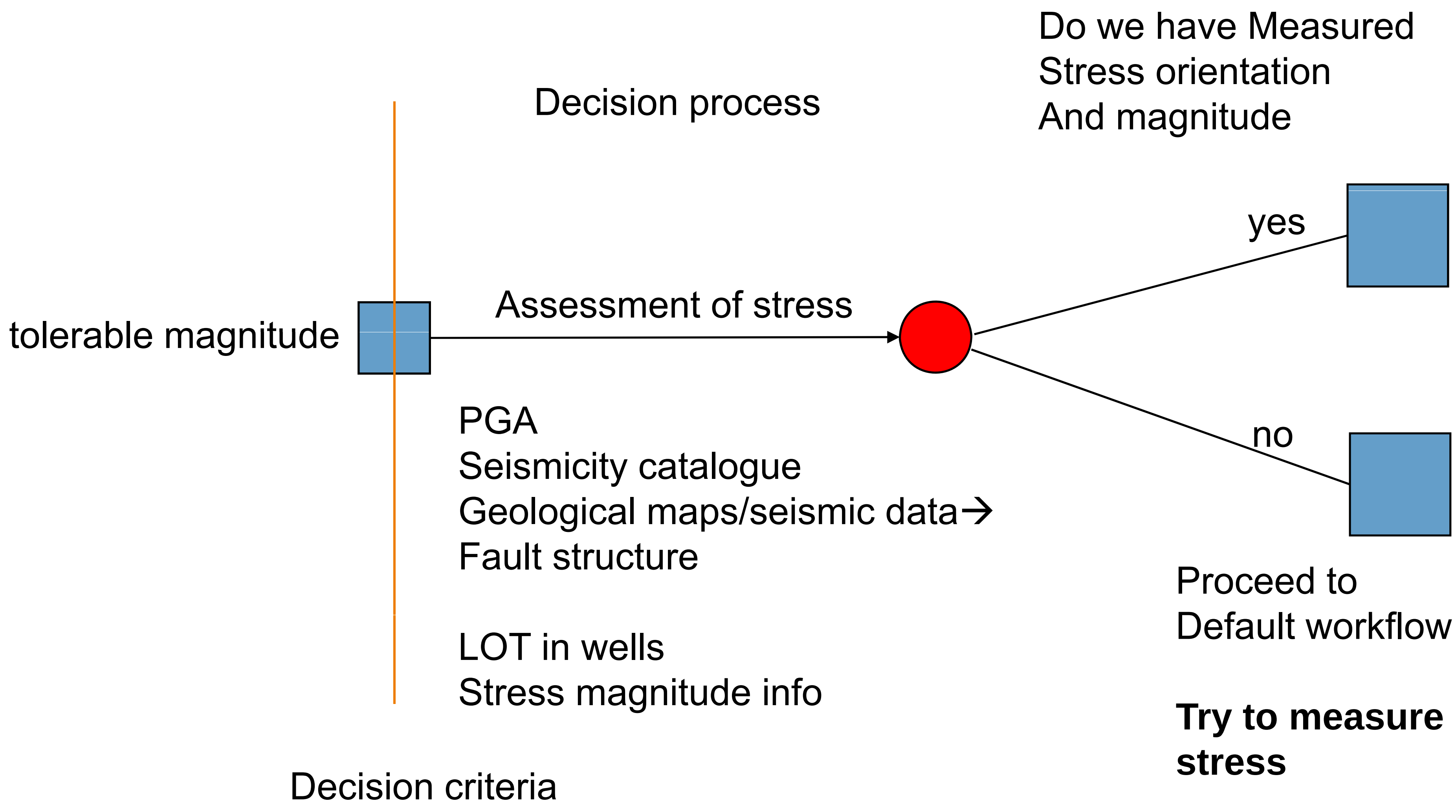
Decision Process



Decision Process (1)



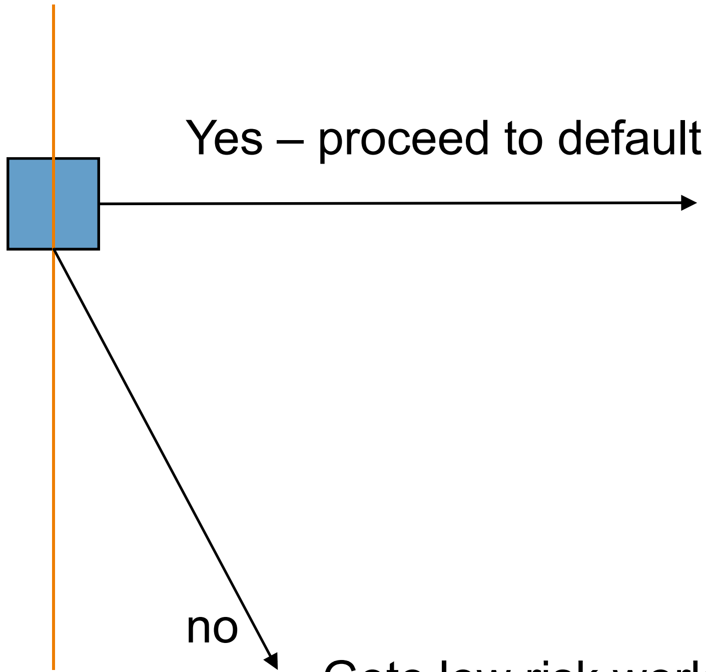
Decision Process (2) –



Decision Process (3) – measured stress

Is it critically stressed (normalized ST/μeff>0.7)
Use conservative μeff= 0.6 (30 degrees friction angle) for volume of 5x5x5 km

In case we have
Measured
Stress orientation
And magnitude

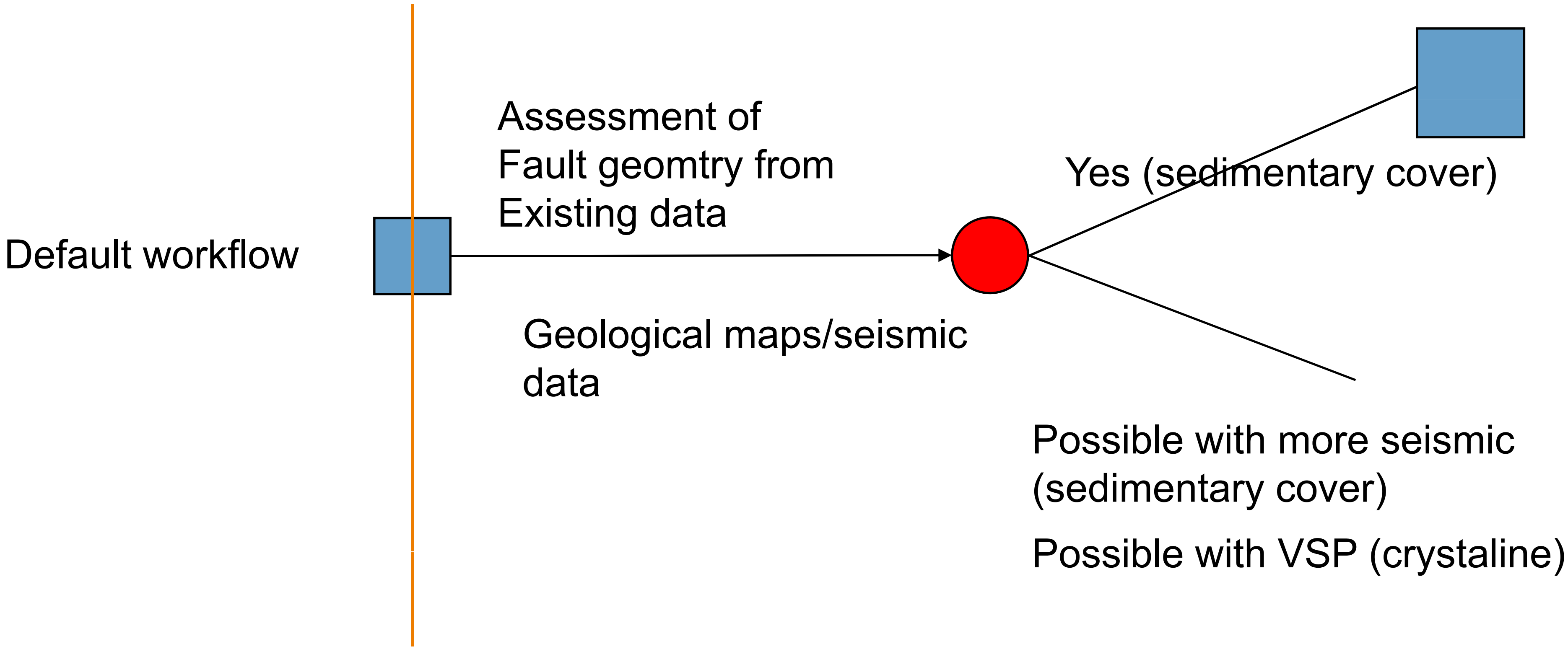


Yes – proceed to default workflow

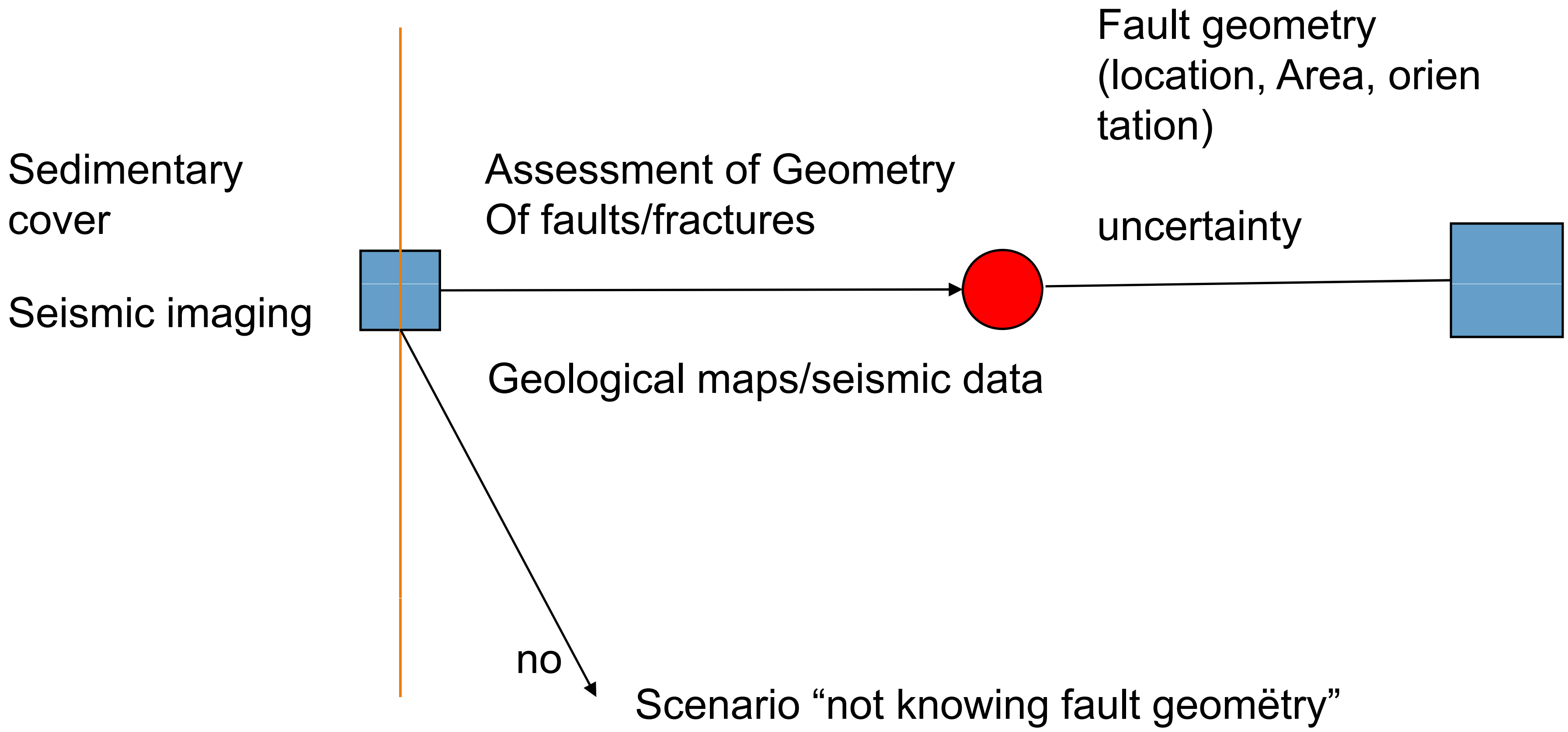
no

Goto low risk workflow

Decision Process (3) –

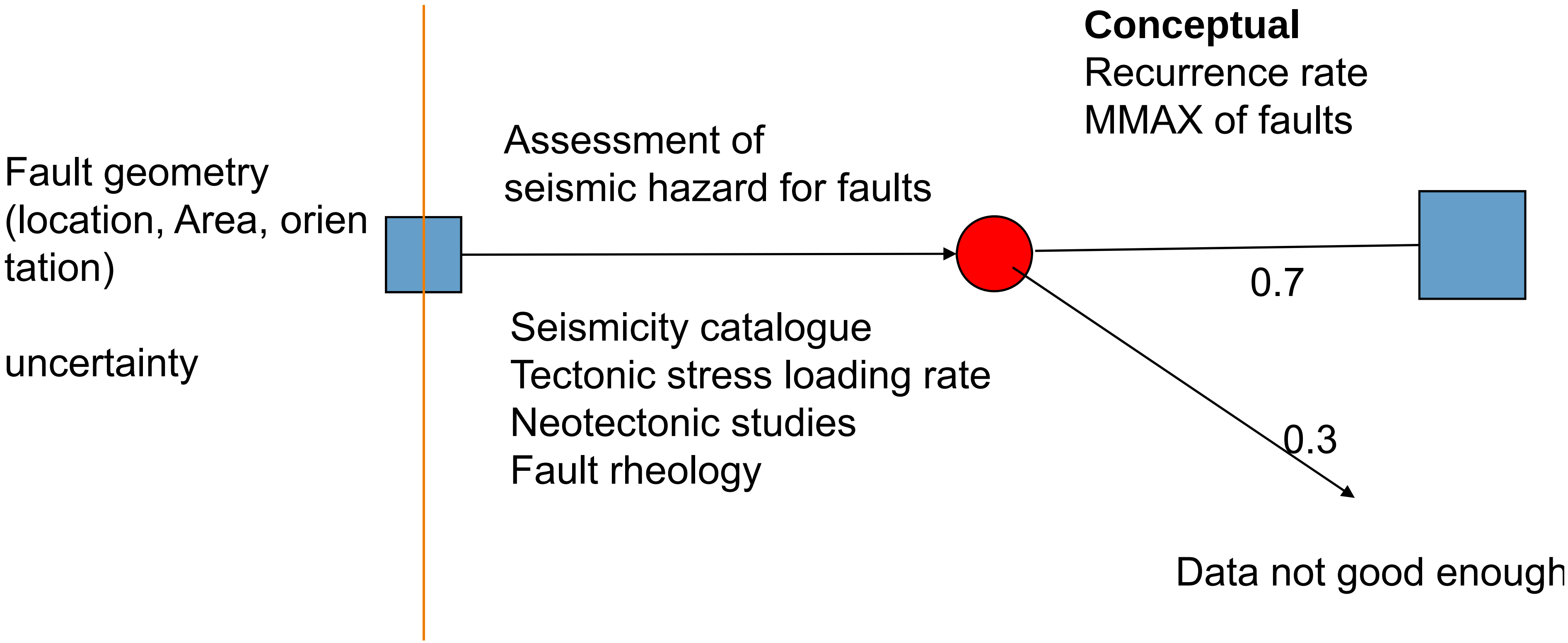


Decision Process (3) – fault geometry



Decision Process (3) – risk of faults

- Slip-Tendency (ST, *fault rheology* + *stress*)
- Fault rheology from neotectonic studies
- Recurrence rate and MMAX on faults (ST+faultarea+PGA)



Decision Process (3) - modelling

Predicted seismicity catalogue

Stress change (x,y,z,t)

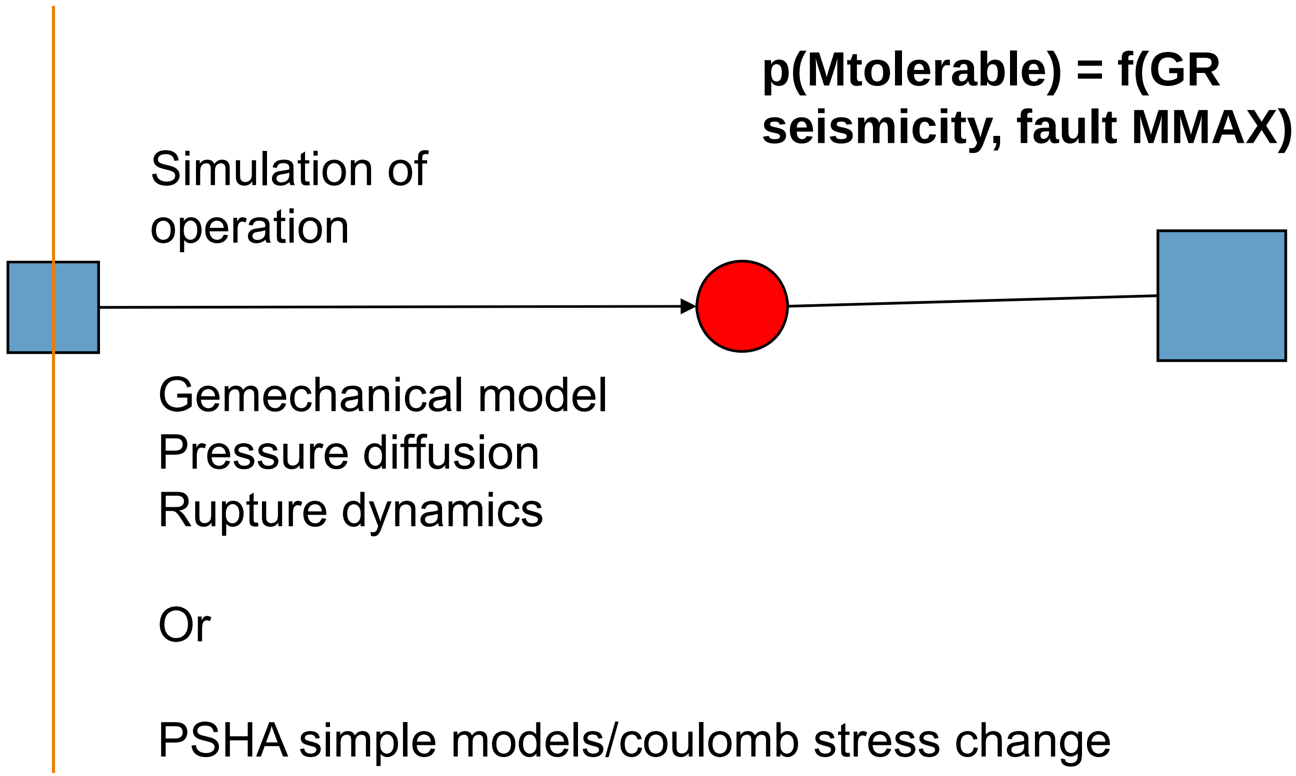
p(Mtolerable) = f(GR seismicity, fault MMAX)

Fault geometry

Fault rheology

uncertainty

Simulation of operation



Gemechanical model
Pressure diffusion
Rupture dynamics

Or

PSHA simple models/coulomb stress change

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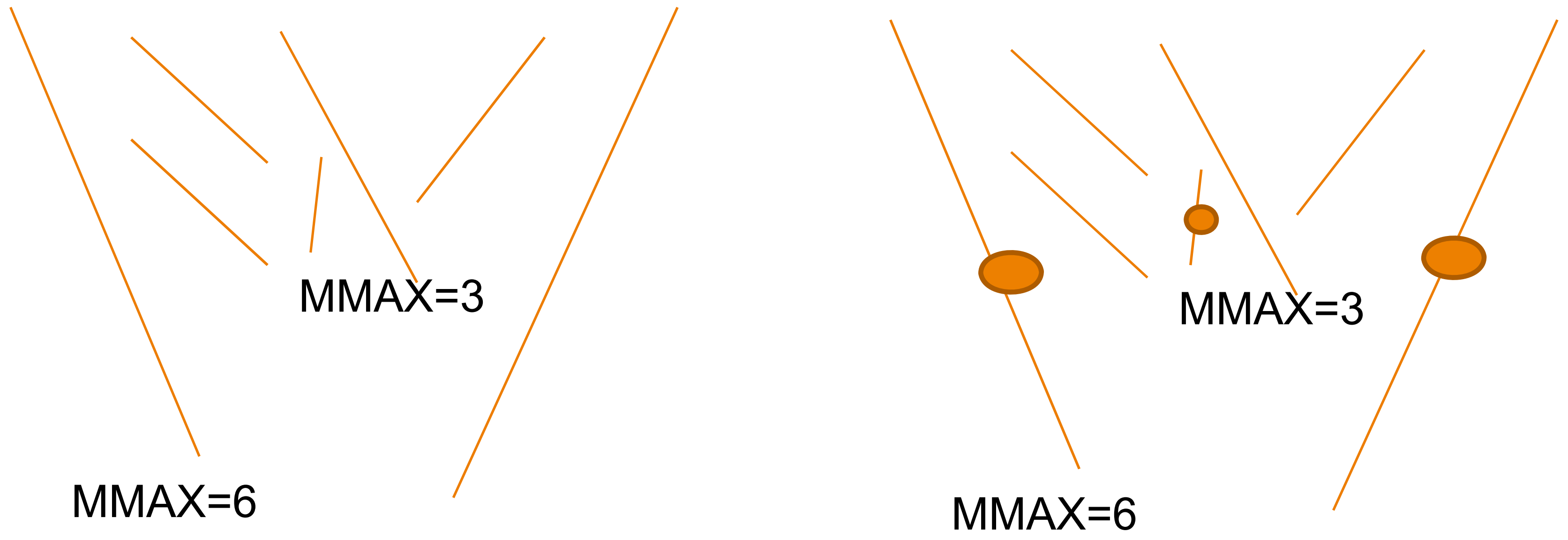
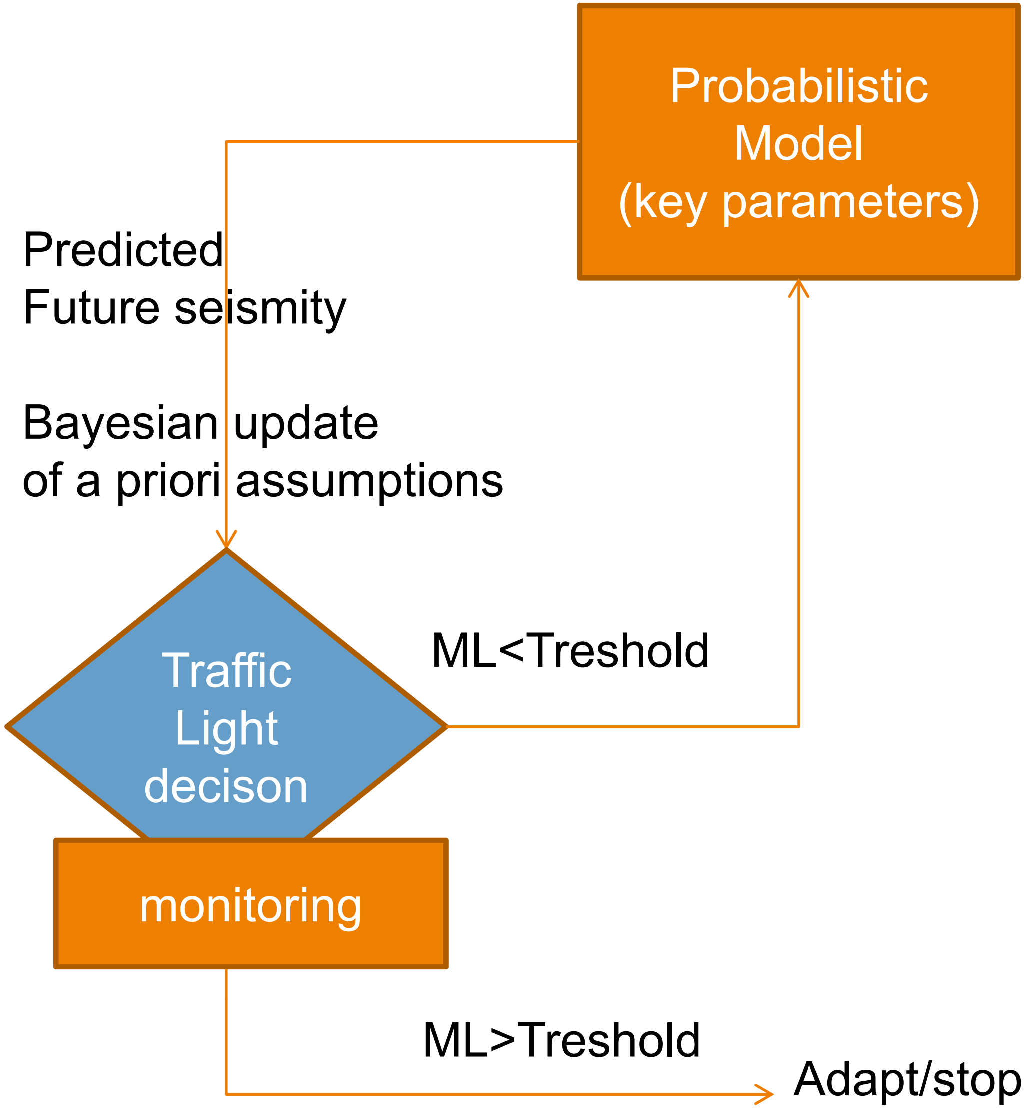
Matching concepts in seed and fault populated models (inverse power-law of fault dimensions)



Dynamic traffic light system: *prediction of seismicity based on key parameters and monitoring sofar*. Treshold ML to stop operations is related to predicted value, not observed ML (**US protocol recommends 0.9 difference**)

Model based/PSHA



Summary

- **What are key parameters ?**
- **Which are the most important?**

- **How can they be practically be used for a) Real-time tools to monitor the evolution of induced microseismicity and b) boundary conditions for regulatory guidelines**
- What are remaining gaps and research needs?