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A coupled fluid flow–seismicity model for real-time assessment of induced seismic hazard and reservoir creation

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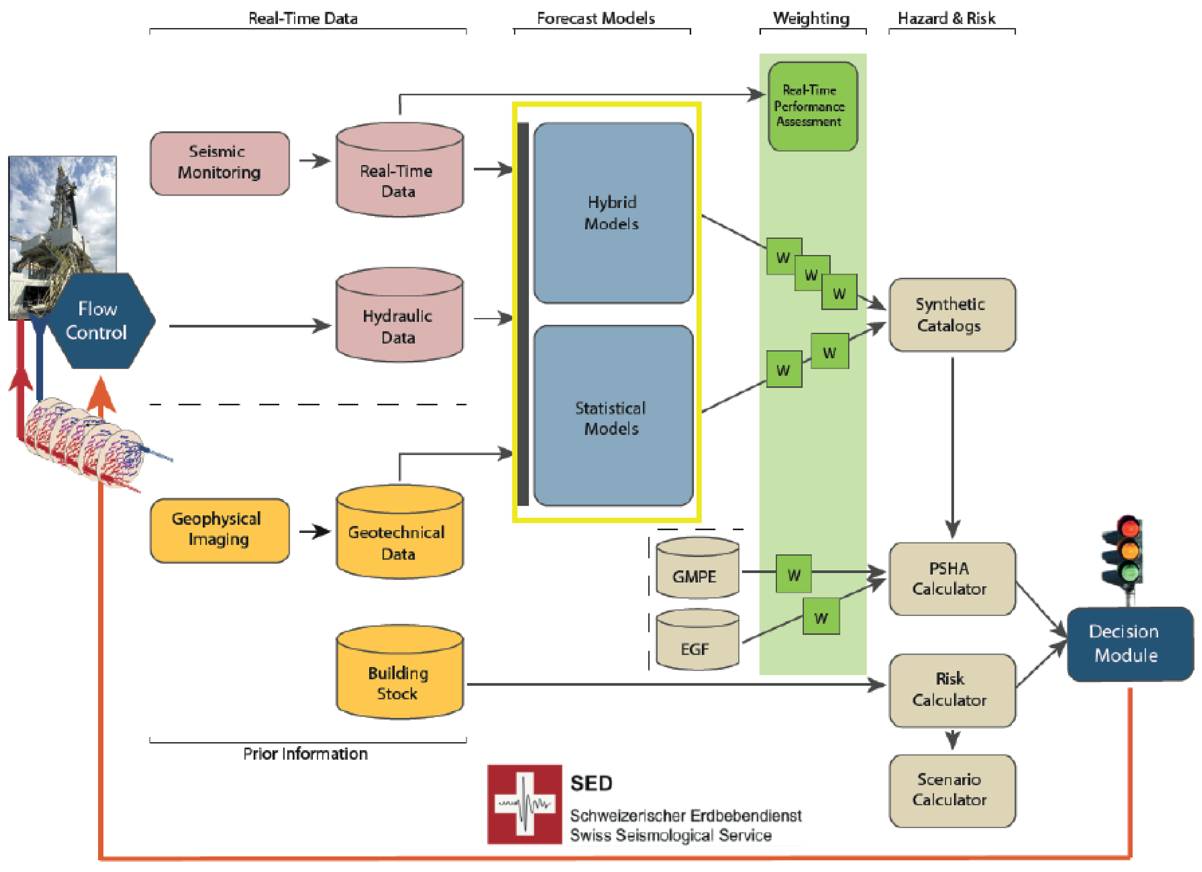
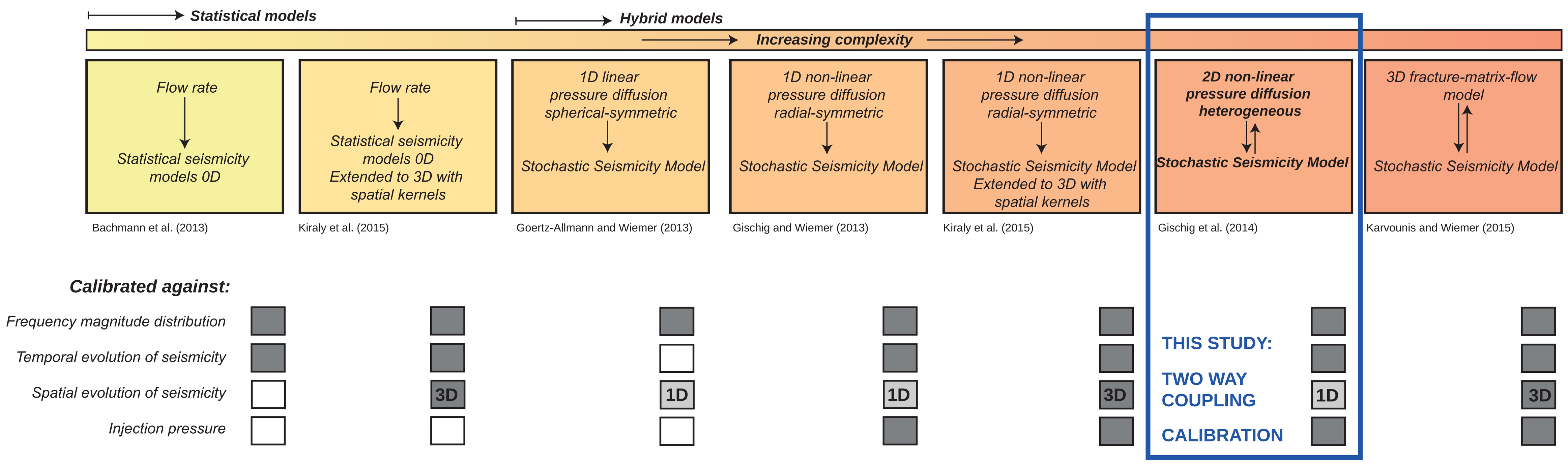
Abstract: *New induced seismicity forecast models are currently being built and calibrated to become part of a real-time hazard assessment tool – the Advanced Traffic Light System ATLS. The models that currently are able to reproduce event numbers and statistics of observed induced seismicity sequences range from basic statistical models to so-called hybrid approaches. In the latter, seismicity is triggered by transient pressure changes modelled by linear or non-linear pressure diffusion models. A severe limitation of the current hybrid models is their loose coupling between seismicity and fluid flow, i.e. they include only one-way coupling from pressure to seismicity, but ignore the feedback of seismicity on the permeability field. We propose a new equivalent continuum fluid flow approach, in which seismicity is triggered by pressure diffusion on potential earthquake hypocenters randomly distributed in space. In addition, two-way coupling is enabled by enhancing permeability in the mesh cells intersected by the source area of the triggered earthquakes. Upon triggering the induced events are assigned a magnitude randomly drawn from Gutenberg-Richter distribution with a pre-defined b-value. The earthquake catalogues thus produced by a stochastic process exhibit a realistic statistical distribution. By enhancing permeability in dependence of slip that is estimated from magnitude and standard earthquake scaling laws, the model yields not only estimates of seismic hazard, but also of the degree of reservoir permeability enhancement obtained by the spent seismic hazard. In the framework of a real-time traffic light system, such a model would not only inform on the current seismic hazard, but also if the required reservoir properties have been achieved. The traffic light system could then be operated with two stop criteria: one based on seismic hazard, the other on based on reservoir size and properties. Here, we present the model procedure along with first results from joint calibration against induced seismicity data as well as wellhead pressure and flow rate as observed during the stimulation at the Basel EGS project in 2006.*

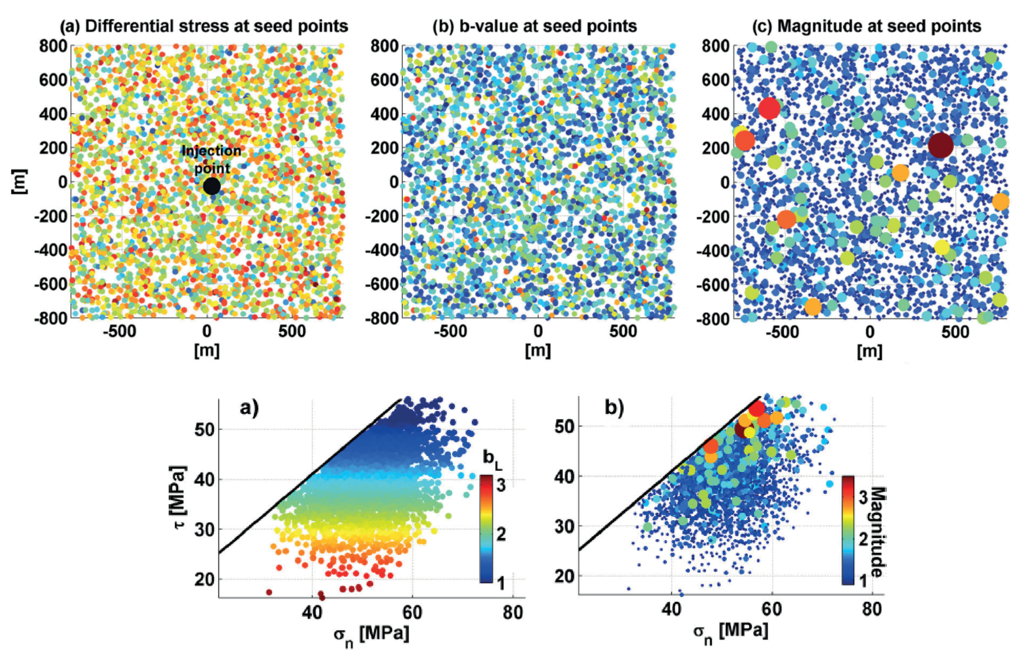
Real-time hazard assessment
The Advanced Traffic Light System (ATLAS)



Forecast Models:



Stochastic seismicity model



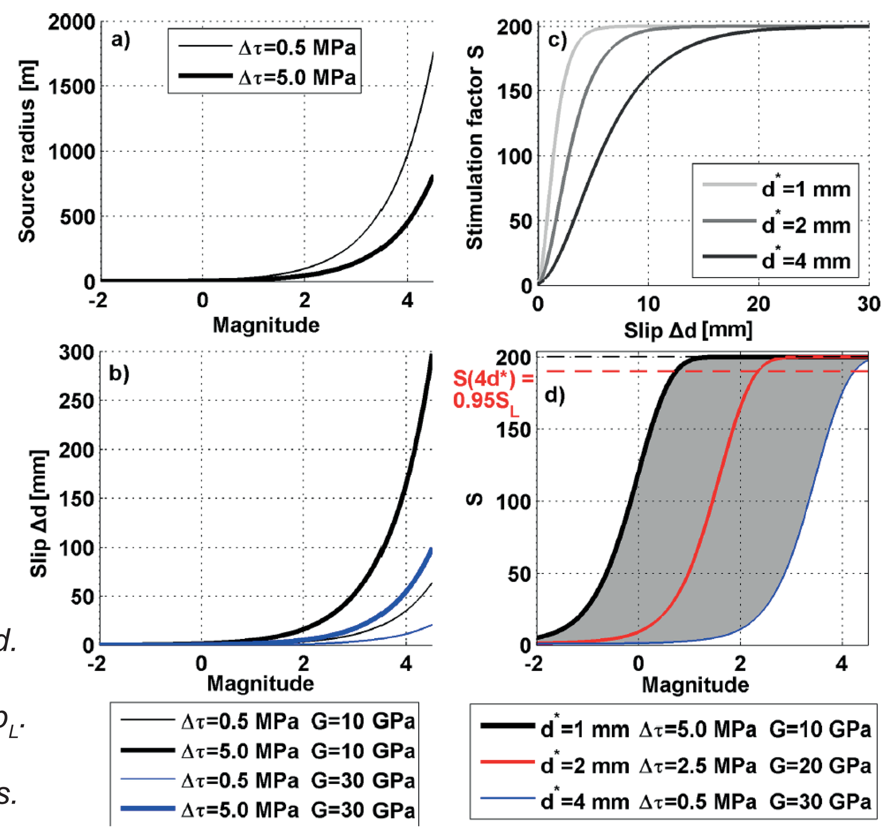
1 If fluid pressure is higher than Mohr-Coulomn failure pressure an earthquake is induced.

2 Magnitude is randomly drawn from a Gutenberg-Richter distribution with local b-value b_L.

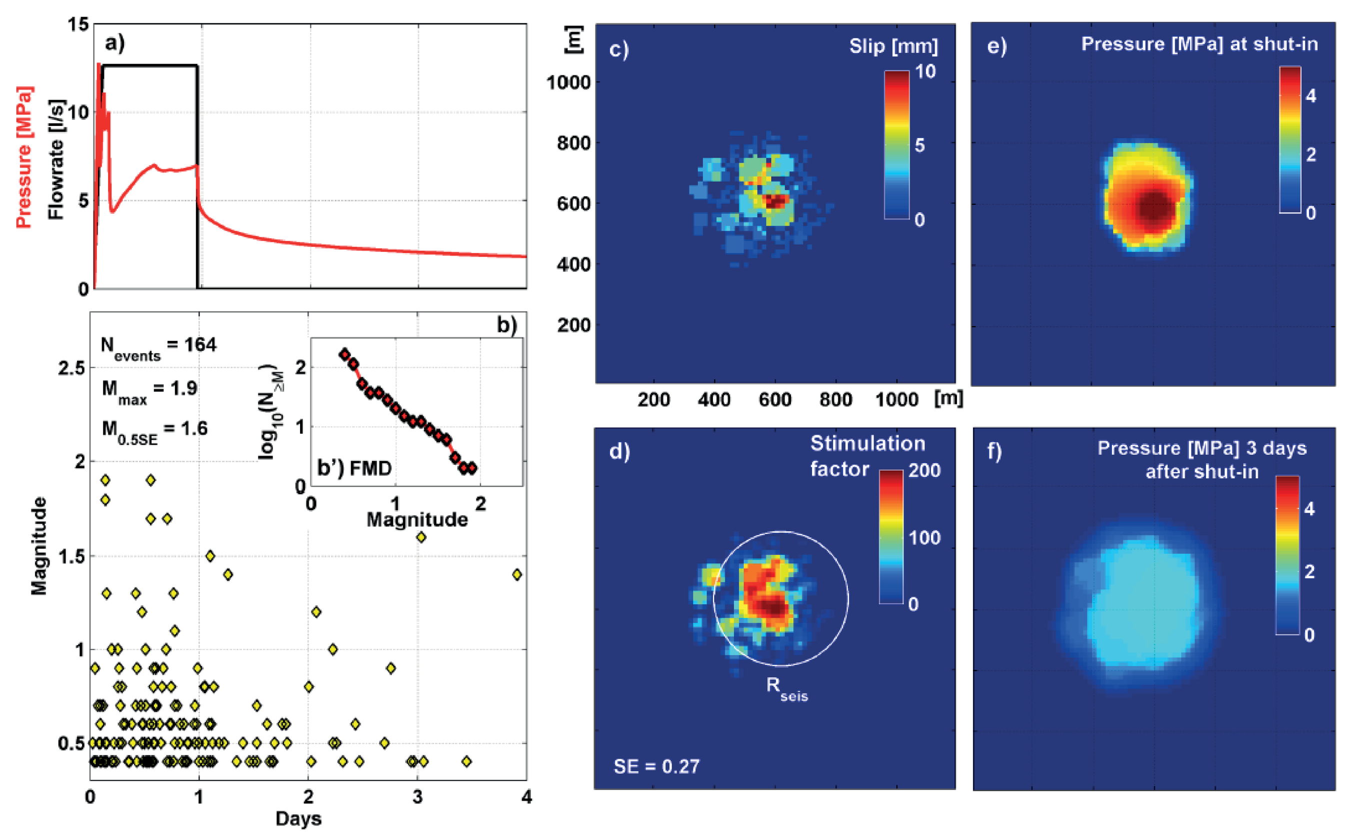
3 Source parameters (source radius, slip distance) are derived from standart scaling laws.

4 Within the source area permeability is increased as a function of slip.

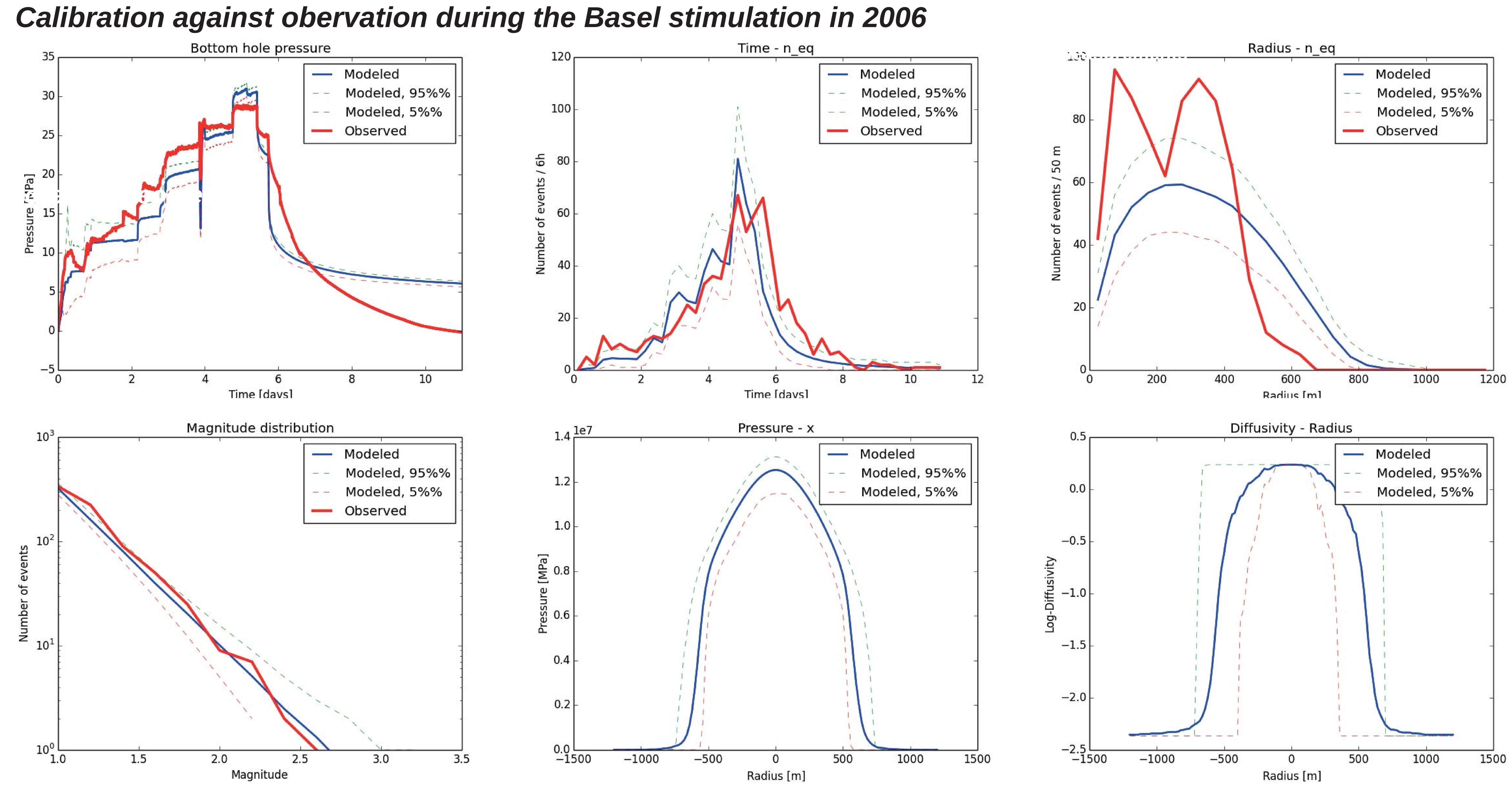
Coupling
Pressure diffusion ⟷ Seismicity model



A single model realization as example



Calibration against obervation during the Basel stimulation in 2006



Two-way coupled simulation implemented in Python using the FiPy software package for the non-linear difdussion simulation and MPI4Py for parallelisation. With the MPI parallelisation, the simulation scales perfectly up to 1000 CPUs (number of forward runs).

All model forecasts (injection pressure, spatial and temporal seismicity evolution, frequency-magnitude-distribution) comes as distribution based on >1000 realizations.

Strongest model sensitivity observed for maximum permeability increase S_L, and M_{min}, the smallest magnitude modelled, and the seed density. M_{min} and seed density are strongly correlated and need to be varied in pairs. We find that it is important to model small earthquakes (0.0 < M < 0.9) that are below the magnitude of completeness, even if the number of earthquakes cannot be compared to the observed catalog.

Required computational resources:

- *One forward model (= 12 days of stimulation): computation time 10 min.*
- *For 1000 realizations: computation time using 48 cores is 3:20 hours on ETH Cluster EULER.*
- *Monte-Carlo calibration against learning period of 1 stimulation days estimated to be 6 hours on 1000 cores (360,000 forward runs).*

Conclusions

- *2D two-way coupled seismicity-fluid flow model can be calibrated against real observations (e.g. in Basel).*
- *Near-real-time performance is possible through massive upscaling*
- *Many application beyond real-time seismic hazard forecasting: e.g. scenario modeling, reservoir design tool.*
- *Design tool: it may be possible to estimate the heat exchanger properties that can be obtained at a predefined level of seismic hazard considered allowable for a project site.*
- *Scenarion models:*
  - *It was shown that less than 10 magnitudes M ≥ 1.5 may contribute as much to permeability enhancement as more than 100 smaller ones.*
  - *At a given site, the achievable permeability enhancement is strongly tied to seismic hazard. Site specific conditions have a much larger impact on seismic hazard than injection strategy.*

References

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In Zusammenarbeit mit der KTI

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