Testing Injection Scenarios with a 3D Discrete Fracture Hybrid Model

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1. Motivation

MODERATING the risk associated with induced seismicity is a necessity, since future scenarios that are free of induced seismicity risk exist neither for reducing the greenhouse emissions nor for reducing the current amount of CO2 in our atmosphere. Here, focus is on induced seismicity generated during the stimulation of Enhanced Geothermal Systems (EGS) reservoirs. The development of this low emissions geothermal technology has suffered by our limited experience from successful EGS stimulations, the complexity of the problem and the high uncertainty regarding the in-situ conditions. It is no surprise that a wide range of opinions regarding the hazard of future injection scenarios exists even among experts. Monte Carlo (MC) simulations can be a remedy to the situation, as they return probabilistic forecasts that consider all possible in-situ conditions and can accurately simulate complicated scenarios for the well accepted physical processes.

2. Forecasting induced seismicity with the 3D Discrete Fracture Hybrid Model

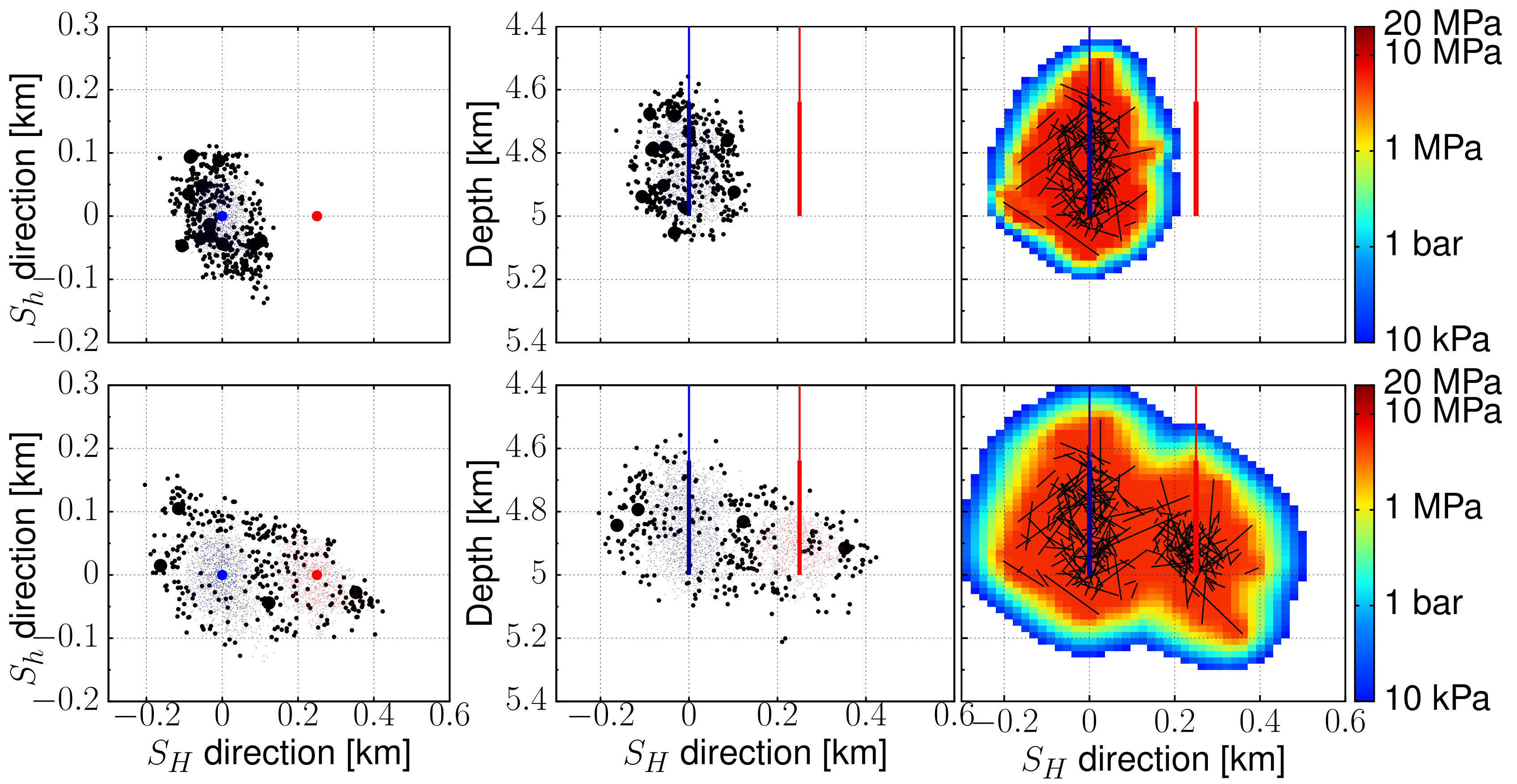

Figure 1: *Synthetic catalog of induced seismicity, discrete fracture network and overpressure obtained from a simulation with the* 3D *Discrete Fracture Hybrid Model (DFHM). Top row highlights events during the Kaizer's effect from the stimulation of the first well, and bottom row from the stimulation of the second well.*

3. Studying Injection Scenarios and Maximizing Reservoir's performance

Three injection strategies are studied by performing MC integration with DFHM. The first strategy is the one injected to the BS-1 well at the EGS project in Basel in 2006. The rest are scenarios where injection happens at four stages; i.e. proportional rates to Basel's in the one (soft), and half the proportional rate for twice the time in the second (softer). Then, the strategy that returns the maximum expected generated electricity over a 25 years period is found.

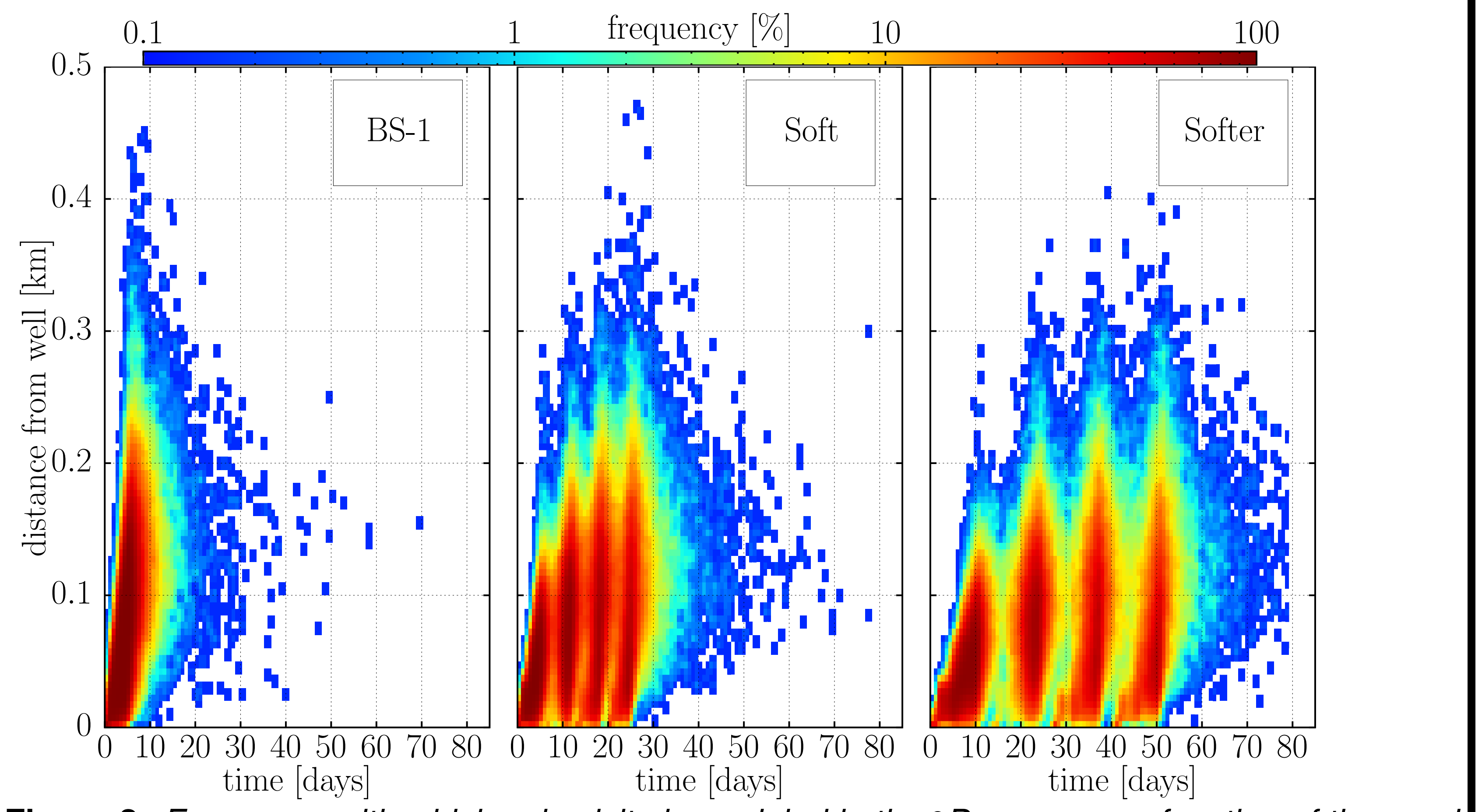

Figure 2: *Frequency with which seismicity is modeled in the* 3D *space as a function of time and distance from the injection well, and for three injection strategies: a Basel like injection (left), a four stages scenario proportional to Basel (middle), and a four stages scenario with longer injections (right).*

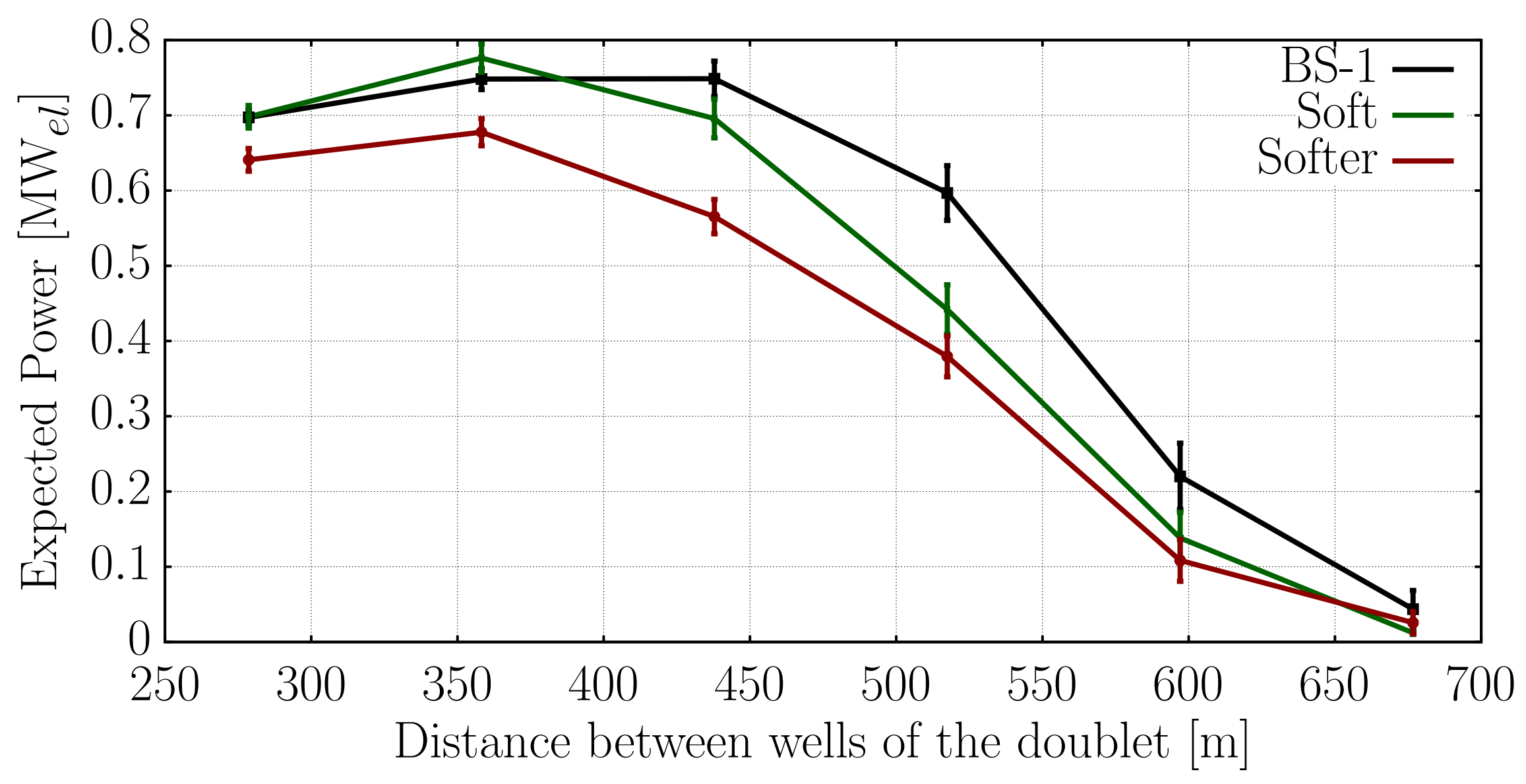

Figure 3: *Expected electrical power produced by a doublet as a function of the distance between its wells and of the injection scenario considered for its wells. After each DFHM simulation, the flow rate that maximizes generated electricity is found and considered for comparing strategies.*

4. Sensitivity Analysis

Sensitivity analysis for the hydraulic properties of DFHM is performed here. 250 sets of seeds are sampled independently and simulated with the reference DFHM parameters. Then, MC integration is performed with the same sets of seeds, but each time one of the modeling parameters differs from the reference set. Statistical properties studied in this sensitivity analysis are the mean number of seismic events from each MC simulation and the median of the furthest simulated hypocenter. For scenarios with significant divergence from the reference's statistical properties, the spatial probability of seismicity occurring at a certain distance is further studied.

Table 1: *Sensitivity analysis for the deterministic modeling parameters of DFHM. Differences larger than* 20% *from the reference are highlighted according to their desirability.*

MC simulation (250 samples)	Mean seismicity ($M_w \geq 0.8$)	Difference from Reference	Furthest Hypocenter (median)
Reference set of parameters	905	-	273 m
$1/4$ less fractures's density	1132	$+25\%$	312 m
$\times 2$ specific storativity (fractures)	536	-40.8%	179.1 m
$\times 10$ specific storativity (fractures)	71	-92.1%	64.7 m
$1/2$ specific storativity (fractures)	2126	$+134\%$	403 m
$\times 2$ permeability of fractures	863	-6.0%	277m
$\times 2$ initial permeability	530	-41.4%	218.1 m
$\times 4$ initial aperture	827	-8.7%	258 m
$\times 2$ post-shearing aperture	1201	$+32.7\%$	312 m
$\times 2$ stress drop	1156	$+27.7\%$	256 m

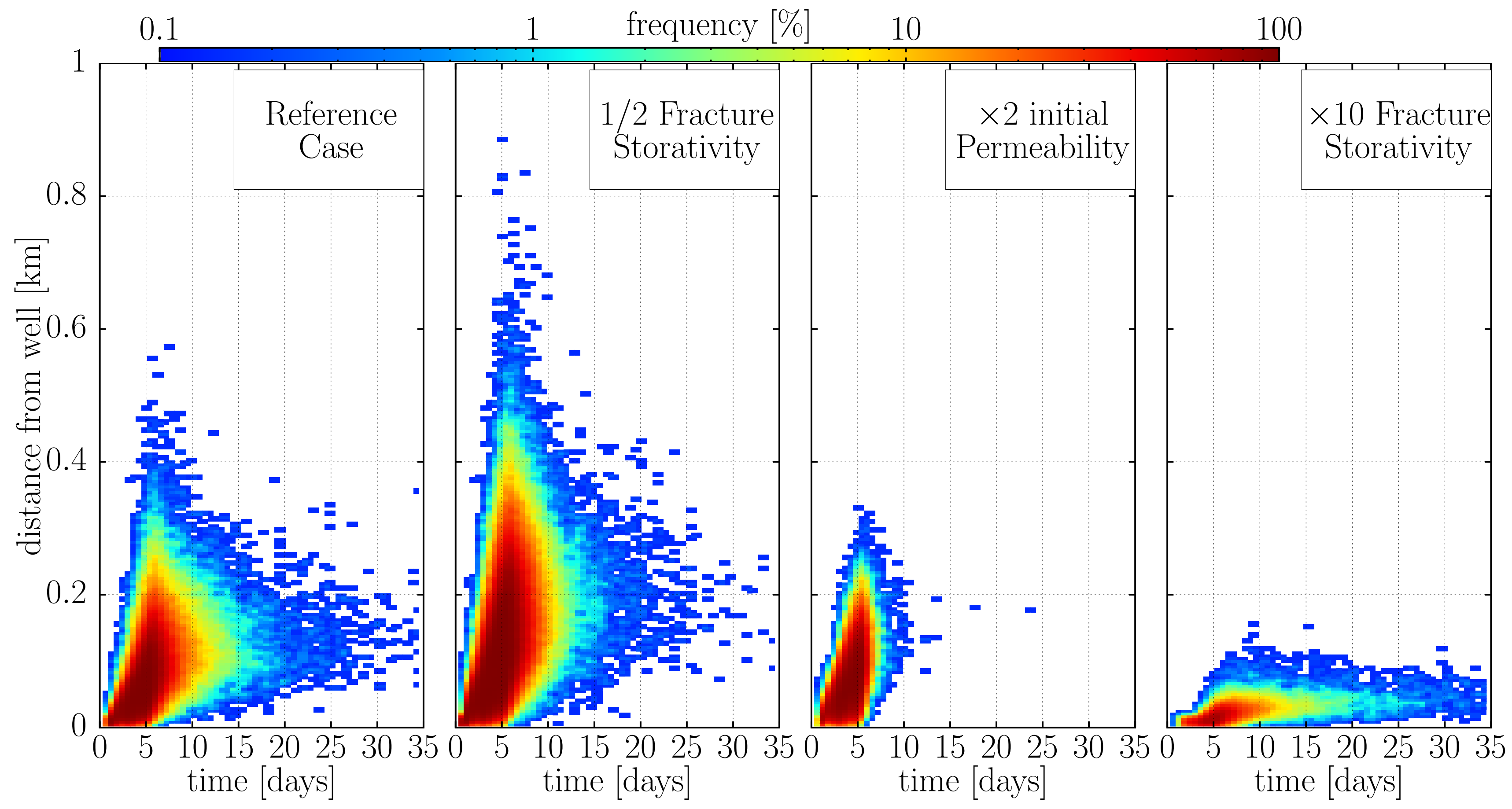

Figure 4: *Frequency with which seismicity is modeled as a function of time and distance from the injection well and with an error* $\approx \pm 3\%$. *On the left, the reference case of the sensitivity analysis is presented. The same plot is shown for the three MC integrations with significant spatial deviation from the reference case.*

5. Accelerating Forecasts

The Platform for Scientific Computing (PASC) funds the optimization of the considered DFHM and brings together scientists from SED, USI university and from the Swiss National Supercomputing Center (CSCS). Significant speedup of approximately two orders of magnitude has been achieved up to now from: from optimizing the coding and employing more efficient algorithms.

- optimizing the coding and employing more efficient algorithms,
- coupling the code with the Utopia and the Eigen libraries,
- pre-processing seeds for faster location of the triggering ones,
- employing features introduced with c++11 (e.g. enumerators) as well as the Counter-Based Random123 Number Generators,
- resolving computational bottlenecks during the updating of the HFR-Sim mesh, and
- optimizing production with Brent's method from the GSL library

Table 2: *Analysis of runtime and speedup for the optimized DFHM and its two main operations.*

(Serial single run)	Initial DFHM	Accelerated DFHM	SpeedUp
Total (s)	8 hours	83 seconds	$\times\mathbf{350}$
Deterministic Solver	4.4 hours	31 seconds	$\times 510$
Stochastic Solver	3.5 hours	20 seconds	$\times 636$

6. Conclusion

Here, results from MC simulations with a three-dimensional Discrete Fracture Hybrid Model (DFHM) are presented. The employed DFHM is expected to be one of forecasting models in the Adaptive Traffic Light System, which is developed by the Swiss Seismological Service and it is expected to be employed in future stimulations in Switzerland and in the European Union. The DFHM already returns in real time not only forecasts of seismicity and of reservoirs performance, but it can also highlight the limitations of the modeled processes in achieving the goals of the stimulation as well as unfavorable reservoir's conditions.

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