A Coulomb stress model to simulate induced seismicity due to fluid injection and withdrawal in deep boreholes

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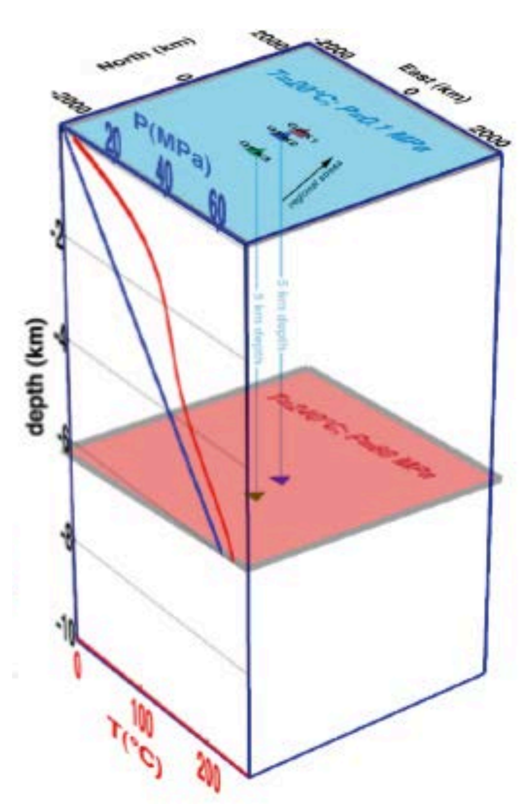
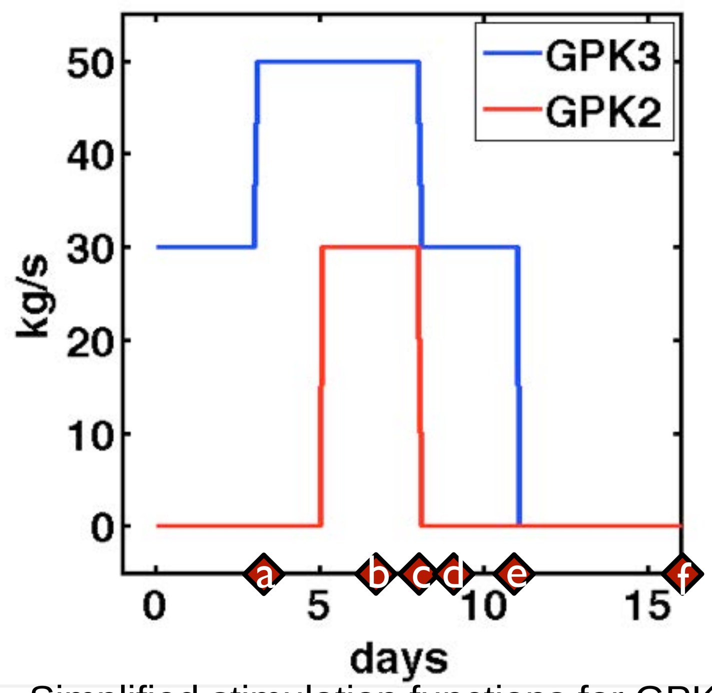
Introduction: Geothermal systems represents a large resource that can provide, with a reasonable investment, a very high and cost-competitive power generating capacity. Considering also the very low environmental impact, their development represents, in the next decades, an enormous perspective. Despite this unquestionable potential, geothermal exploitation has always been perceived as limited, mainly because of the dependance of a site usefulness on several pre-existing conditions, mainly correlated to the reservoir rock's permeability and porosity, the amount of fluid saturation and, first of all, a convenient temperature-depth relationship. However, this major barrier it is not insurmountable and a notable progress in recent tests is achieved with the Enhanced Geothermal System (EGS), where massive fluid injection and withdrawal were performed to enlarge the natural fracture system of the basement rock. The permeability of the surrounding rocks results highly increased by pressurized fluids circulation and geothermal resources, in such way, become accessible in areas where deep reservoir exploitation, otherwise, could be not advantageous or even possible. Still problematic remains, however, most of the key technical requirements as, firstly, deep fluid injection, that represents a necessary field practice in EGS development. This kind of procedure have often strong and uncontrolled physical effects on the neighboring environment, involving possibly even large areas and, in particular, they represent one of the most important sources of seismicity induced by human activities. In some cases, seismicity reaches level that can not be sustained, as in the paradigmatic case of the 2006 M=3.4 earthquake induced in the Basel city (Swiss), with the consequent EGS project early termination.



Sketch of the 3D simulated volume. Wells positions (triangles) and pressure/ temperature initial conditions (blue and red lines) are reported. Direction of regional stress field superimposed is also shown (black arrow).



Simplified stimulation functions for GPK2 and GPK3 Soultz-sous-Forêts wells, representing the rates of injected water. Letters from a to f refer to the times of the stimulation cycle shown.

Method and results.

Our method of analysis consists of a two-step procedure. In the first step, injection or withdrawal of water is simulated (Pruess, 1991). The modeled 3D physical domain and the imposed initial conditions are shown. Water at ambient condition is withdrawal or injected at a chosen rate in a point located at -5 km depth. In such a way we obtain the pressure and temperature changes at each point in the medium, subsequentely considered as mechanical sources, heterogeneously distributed in the whole discretized Volume, which generate an incremental stress tensor field estimated by using the Comsol Multiphysics finite element code (Troiano et al., 2011). Once the complete field of stress changes is computed, Coulomb stress changes on a given fault plane in the volume are computed on the favorably oriented fault planes, i.e. on which the total Coulomb stress, including the tectonic stress plus the incremental stress due to withdrawal/injection of water reach its maximum value (Troise et al., 1999).

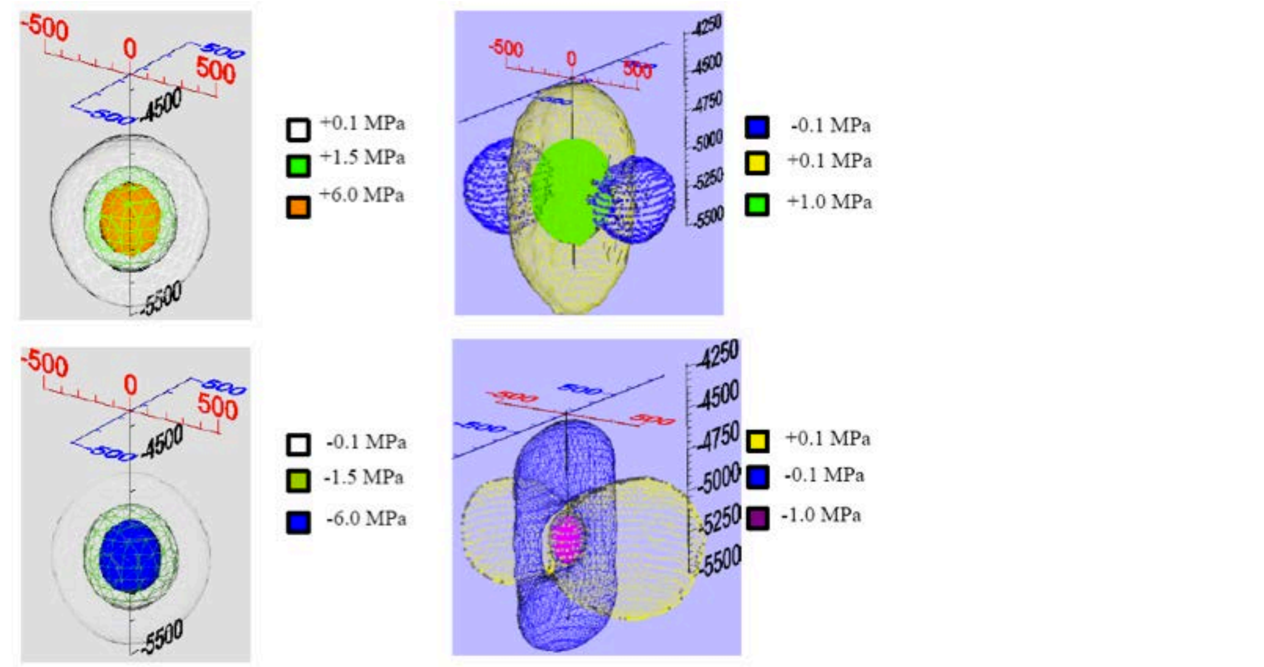
We have applied our procedure for two distinct cases:

a. a continuous water injection (and withdrawal) at fixed rate of 50 kg/s in a homogeneously permeable medium. Effects in terms of Coulomb stress changes are shown.

b. a real case reproduction. We reproduce the joint stimulation of two distinct wells (named GPK2 and GPK3) realised in the Soultz.-sous-Foret geothermal site and accurately reported in Baria et al. (2004). The simulated injection history and results in terms of over-pressurization and Coulomb stress changes over the whole volume are shown. Comparison between Coulomb stress changes and induced seismicity observed is also reported along an horizontal plane passing for the injection point.

In both cases,a background tectonic stress coherent with the one estimated for the Soutz-sous-Foret area is imposed.

We propose, in such a way, a procedure to estimate how the potential for failure along regions of the geothermal reservoir changes due to well stimulation.

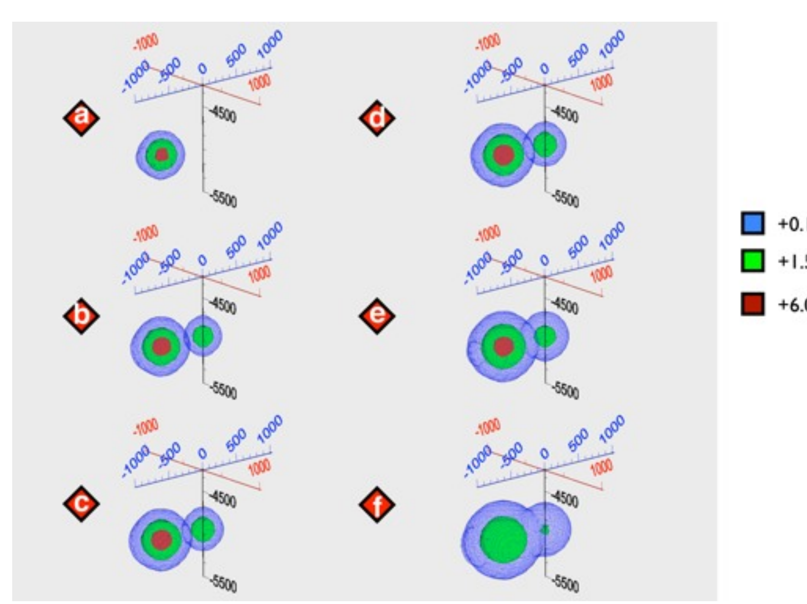


Pressure changes (left) and maximum Coulomb stress changes (right) resulting from injection (upper) and withdrawal (lower) of 50 kg/s of water, at 5 km of depth, in a homogeneous medium with permeability 10^{-16} m^2.

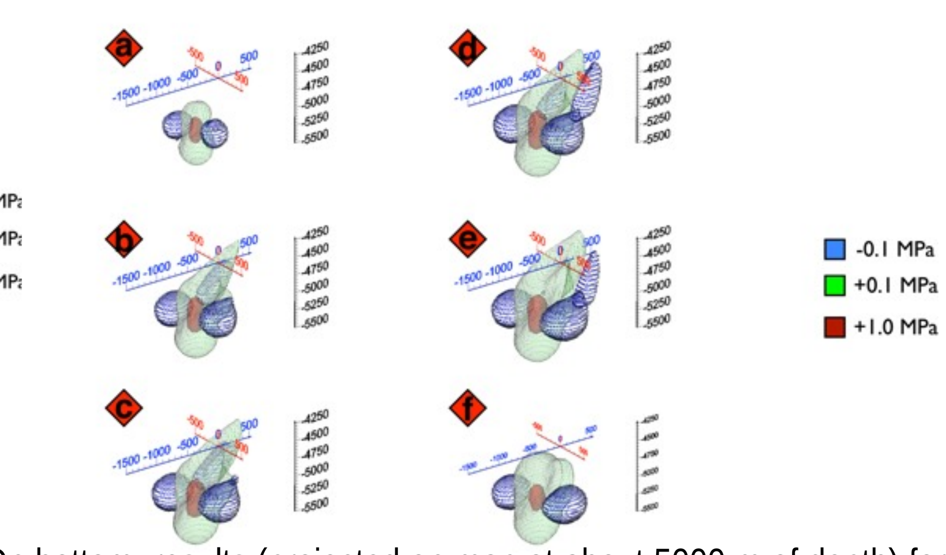
Discussion.

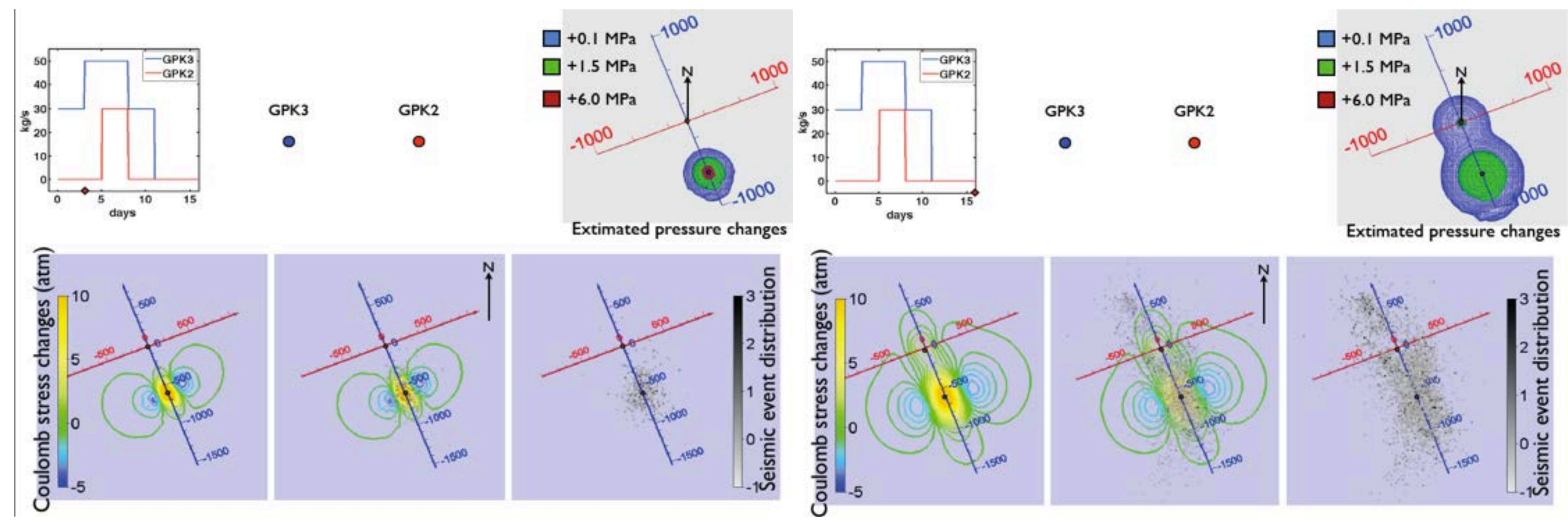
Our results show a very good agreement between modeled maximum Coulomb stress changes and observed seismicity, as evident in the comparison shown. In particular the N-S distribution of the seismic events is retrieved, with the correct alignment along the two wells. Noteworthy, at time *a*, after 4 days of continuos water injection just in the GPK3 well, while the overpressure pattern still retains a spherical symmetry, the Coulomb stress changes already presents an elongated behavior. Being the GPK2 well still shut off, this effect can be related just to the pre-existing loading of the regional stress field. On other hand, at the end of our simulation, at time *f*, this elongation effect of the Coulomb stress changes pattern results enhanced and a similar behavior appears also in the Pressure changes. This indicates that the N-S distribution of the seismic cloud results enhanced by the joint stimulation effects. The pressurized front, and the associated increase of the Coulomb stress levels, continue to expand also after both wells are shot out, and this effect matches with the persistency of induced seismicity and the peripheral distribution of the events, associated from [*Baria et al.*, 2004] to a buoyancy effect. We show in figures such agreement only for initial and final stimulation times, it remains optimal also in the intermediate ones.

On the grounds of our results, it appears that the main causes of induced seismicity during stimulation are the Coulomb stress changes generated by water injection. Actually, this model, besides constituting an important step towards interpretation and mitigation of induced seismicity, could be equivalently used for a better planning of reservoir stimulation as well as to forecast the areas of higher likelihood for induced seismicity.



On top: astimated pressure changes (left) and maximum Coulomb stress changes (right) for the different phases of the injection experiment. Numbers from 1 to 6 refer to the times of the stimulation cycle shown.





On bottom: results (projected on map at about 5000 m of depth) for pressure and maximum Coulomb stress changes after the first three days of stimulation of GPK3 well (left) and after the end of stimulation cycle of the two wells (right). The reference system is rotated along the direction passing between the two wells. Coulomb stress changes are compared with seismicity occurred in the two periods. Note the good agreement between positive stress changes and seismic areas.

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