Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

3D Models for Stress Changes and Seismic Hazard Assessment in Geothermal Doublet Systems in The Netherlands

Jan-Diederik van Wees[1,2] Siavash Kahrobaei[1], Sander Osinga[1], Brecht Wassing[1], Loes Buijze[1,2], Thibault Candela[1], Peter Fokker[1,2], Jan ter Heege[1], Mark Vrijlandt[1]

[1]TNO – Geological Survey of the Netherlands, Princetonlaan 6, 3584 CB Utrecht

[2]Universiteit Utrecht

Jan_diederik.vanwees@tno.nl

Keywords: Induced seismicity, geomechanics, hydrothermal models.

ABSTRACT

The role of geothermal energy production as a source of a sustainable energy for district heating in the Netherlands is expected to grow, from 20 geothermal doublets currently in operation to around 175 doublets in 2030 . Current geothermal doublets and planned doublets produce from porous sandstone aquifers of Tertiary, Cretaceous/Jurassic, Permian (Rotliegend), and Triassic age and fractured carbonate rocks of Dinantian age. Production temperatures of the conventional doublets are generally between 65 – 100 °C, and fluids are re-injected at temperatures between 20 - 45°C. Cooling of reservoir rocks and surrounding rock mass can lead to significant thermal stresses, which, superimposed on the pressure induced stress changes, may affect fault stability and may lead to an increased seismicity hazard. In particular, doublets drilled in competent rock types and marked by large temperature contrasts are prone to a high likelihood for the build-up of significant thermal stresses over time (>>1MPa). For safe and effective operations, it is important to assess the long-term combined effect of pore pressure and temperature changes in geothermal operations on fault stability and associated seismicity, taking into account (1) operational parameters such as injection temperatures, pressures, flow rates volumes and (2) in-situ geological, geohydrological and geomechanical factors.

We developed a 3D workflow, capable of assessing both pressure and thermal evolution and its effects on stress changes on faults, which can be used to evaluate seismic hazard. The workflow is designed for complex faulted reservoirs, taking into account the afore-mentioned operational and in-situ factors. The workflow easily quantifies the effect of long-term cooling during geothermal operations on fault stresses, which can be used for fault reactivation potential and seismic hazard, for typical conventional geothermal doublets. In this paper the workflow is demonstrated for relatively simple reservoir geometries in the most common geological settings in The Netherlands, i.e. homogeneous porous sandstone reservoir (representative of the Cretaceous/Jurassic, Rotliegend and Triassic reservoirs in the south-western and northern part of The Netherlands).

Results for homogeneous and faulted porous sandstone reservoirs indicated that geothermal doublet operations, can cause thermal stressing causes a significant increase of Coulomb stresses and can have a destabilizing effect on fault stability within the vicinity of the geothermal doublets. Increased pore pressures can cause additional positive Coulomb stressing of the faults; however, the effect of pore pressure is limited in areal extent and relatively small compared to the effect of thermal stresses, except in the first years of operation.

1. INTRODUCTION

Geothermal Energy in The Netherlands is expected to grow, from 20 geothermal doublets currently in operation to around 175 doublets in 2030 ((Stichting Platform Geothermie et al, 2018). Most Existing geothermal doublets and planned doublets produce from porous sandstone aquifers of Tertiary, Cretaceous/Jurassic, Rotliegend and Triassic age and fractured carbonate rocks (van Wees et al, 2017), whereas two doublet systems have been developed in rocks of Dinantian age. Production temperatures of the conventional doublets in a depth range of ca 2 to 3 km are generally between 65 – 100 °C. Fluids are re-injected at temperatures between 20 - 45°C. Cooling of reservoir rocks and surrounding rock mass can lead to significant thermal stresses, which, superimposed on the pressure induced stress changes, may affect fault stability and may lead to an increased seismicity hazard. For safe and effective operations, it is important to assess the long-term combined stress effect of pore pressure and temperature changes in geothermal operations on fault stability and associated seismicity, taking into account (1) operational parameters such as injection temperatures, pressures, flow rates volumes and (2) in-situ geological, geohydrological and geomechanical factors.

Here we present a 3D workflow, capable of assessing both pressure and thermal evolution and its effects on stress changes on faults, which (due to its computational performance) can be used for probabilistic assessment of stress and hazard assessment, designed for complex faulted reservoirs taking into account the afore-mentioned operational and in-situ factors. The workflow extends on a numerical method recently published (Van Wees et al., 2019). It quantifies the effect of long-term cooling during geothermal operations on fault stresses.

The method is demonstrated for relatively simple reservoir geometries in the most common geological settings in The Netherlands, i.e. homogeneous porous sandstone reservoir in the south-western and northern part of the country..

2. METHODS

Building geomechanical models for complex reservoirs poses a major challenge, in particular if many faults need to be included. We recently developed a novel way of calculating induced stress changes and associated seismic moment response for structurally complex reservoirs with tens to hundreds of faults (Van Wees et al., 2019). The capability of the approach, dubbed as MACRIS (Mechanical Analysis of Complex Reservoir for Induced Seismicity) has been proven through comparisons with finite-element-models (FEM). MACRIS is a TNO-proprietary tool which allows for the evaluation of the poro-elastic stress evolution for complex reservoirs, marked by faults offsetting the reservoir layer (Figures 1,2). It takes into account both pressure and thermal changes and uses standard reservoir simulator outcomes as its input. MACRIS employs a mesh-free method for the stress solution which allows for high resolution stress solution at faults. The stress solution is based on semi-analytical approaches for solving the stress effects as a function of volumetric changes related to pressure and thermal change in the reservoir simulation grid. The method has been extensively described in Van Wees et al (2019) for pressure changes.

To extend the method for thermal effects, the thermal and pressure related stress for a point source marked by a finite volume dV, volumetric expansion factor β, temperature change ΔT and pressure change ΔP is calculated in MACRIS using inflation point sources (Okada, 1992). The volumetric inflation ΔV (positive for $\Delta T, \Delta P > 0$) is given by:

$$\Delta V = (\varepsilon_{Tz} + \varepsilon_{Pz}) \, dV \quad (1)$$

$$\varepsilon_{Tz} = \frac{(1+\nu)}{(1-\nu)} \Delta T \, \beta/3 \quad (2)$$

$$\varepsilon_{Pz} = \frac{(1-\nu-2\nu^2)}{(1-\nu)E} \Delta P \quad (3)$$

The stress effects are calculated on the faults represented in the reservoir model by fault pillars and uses an octree representation of the inflation sources for computational efficiency (Van Wees et al., 2019; Figure 2).

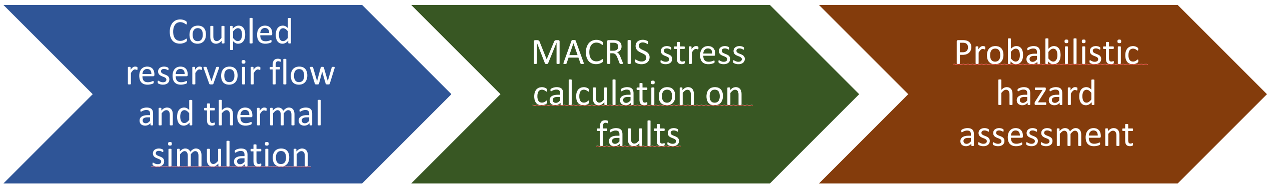

Figure 1: Workflow Approach for Coupling Reservoir Simulation Results to Mechanical Analysis and Probabilistic Hazard Assessment

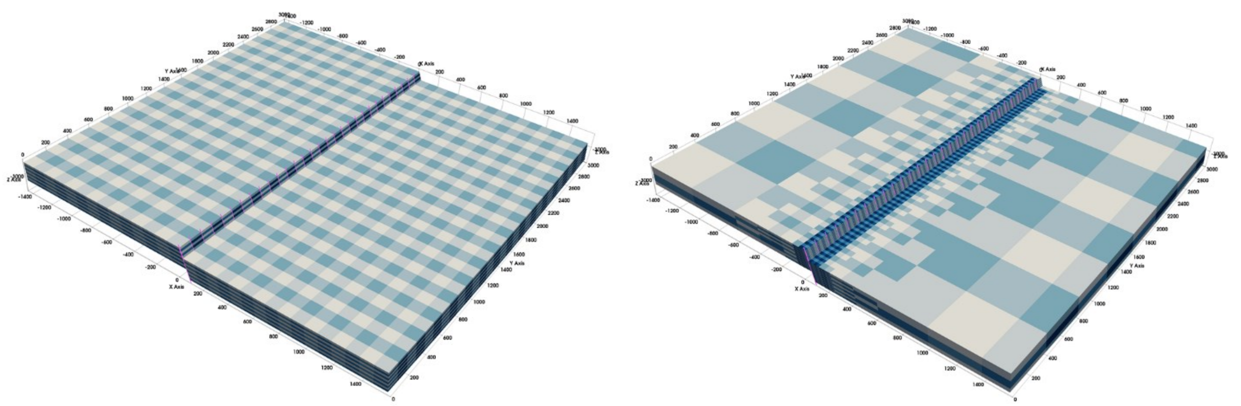

Figure 2: Schematic Regular Reservoir Model Grid Representation for the Flow Simulation with a Single Fault (Left), and Octree Representation of the Same Grid for the Stress Calculation in MACRIS (Right). The Stresses are Calculated at Fault Pillars (Denoted by Evenly Spaced Purple Lines in the Dip Direction of The Fault) (Source: Van Wees et al., 2019).

In this paper, the flow simulations have been performed for doublet systems with a well distance of 1500m at reservoir level at ca 2500m depth (cf. Van Wees et al, 2012). The flow simulations have been performed with the Open Porous Media simulator (OPM) which is well suited for single phase coupled 3D flow and thermal simulation for geothermal reservoirs (Kahrobaei et al., 2019). The grid dimensions have been chosen at 5x5 km, with a 100 m thick reservoir, and including a very low permeability (0.1mDarcy) overburden and underburden for the thermal simulation. The cells in the grid are 50 m in the horizontal x and y directions, and are 10 m thick, resulting in 300k cells. The reservoir has been faulted by a single fault for which different throw scenarios have been considered. Case 1 corresponds to a throw of half the thickness of the reservoir, with the doublet flow crossing the fault (Figure 3). Case 2 is marked by no throw. In case 3, the throw equals the reservoir thickness such that the fault corresponds to a no flow boundary. In this case both the doublet wells are positioned in the **footwall fault block at reservoir level. All cases adopted hydrothermal** and mechanical parameters as listed in Table 1. Case 2 can also be compared with the analytical solution of the horizontal stress change $\Delta\sigma_{xx}$ and change in coulomb failure function ΔCFF (coulomb stress change) for an infinite cooling aquifer, which amounts to $\Delta\sigma_{xx} = \frac{E}{(1-\upsilon)}\Delta T\,\beta/3$, and $\Delta CFF = -(0.5\Delta\sigma_{xx} + \tan(\varphi)\,\Delta\sigma_{xx})$.

Table 1: Hydrothermal and Mechanical Parameters for the Flow Simulation and MACRIS.

Parameter	*Symbol*	*Value*	*unit*
Young's modulus	*E*	*18*	*GPa*
Poisson's ratio	*v*	*0.18*	*-*
Volumetric thermal expansion coefficient	β	*3x10*$^{-5}$	*K*$^{-1}$
Top depth reservoir	*-*	*2400*	*m*
Thickness reservoir	*D*	*100*	*m*
Permeability reservoir	*k*	*300*	*mD*
Porosity Reservoir		*0.15*	*-*
Fluid density	ρ_f	*1050*	*kgm*$^{-3}$
Fluid viscosity	μ	*2x10*$^{-4}$	*Pa s*
Fluid thermal conductivity		*0.6*	*W m*$^{-1}$ *K*$^{-1}$
Fluid heat capacity		*4.18*	*kJ kg*$^{-3}$ *K*$^{-1}$
Rock heat capacity		*2700*	*kJ m*$^{-3}$ *K*$^{-1}$
Rock thermal conductivity		*4*	*W m*$^{-1}$ *K*$^{--1}$
Bulk Rock density	ρ_r	*2260*	*kgm*$^{-3}$
Friction angle	φ	*30*	*degrees*
Fault dip	*-*	*70*	*degrees*
Horizontal to vertical effective stress ratio	$K0_{eff}$	*0.6*	*-*
Initial minimum to maximum horizontal stress ratio	*Sh/SH*	*0.9*	*-*

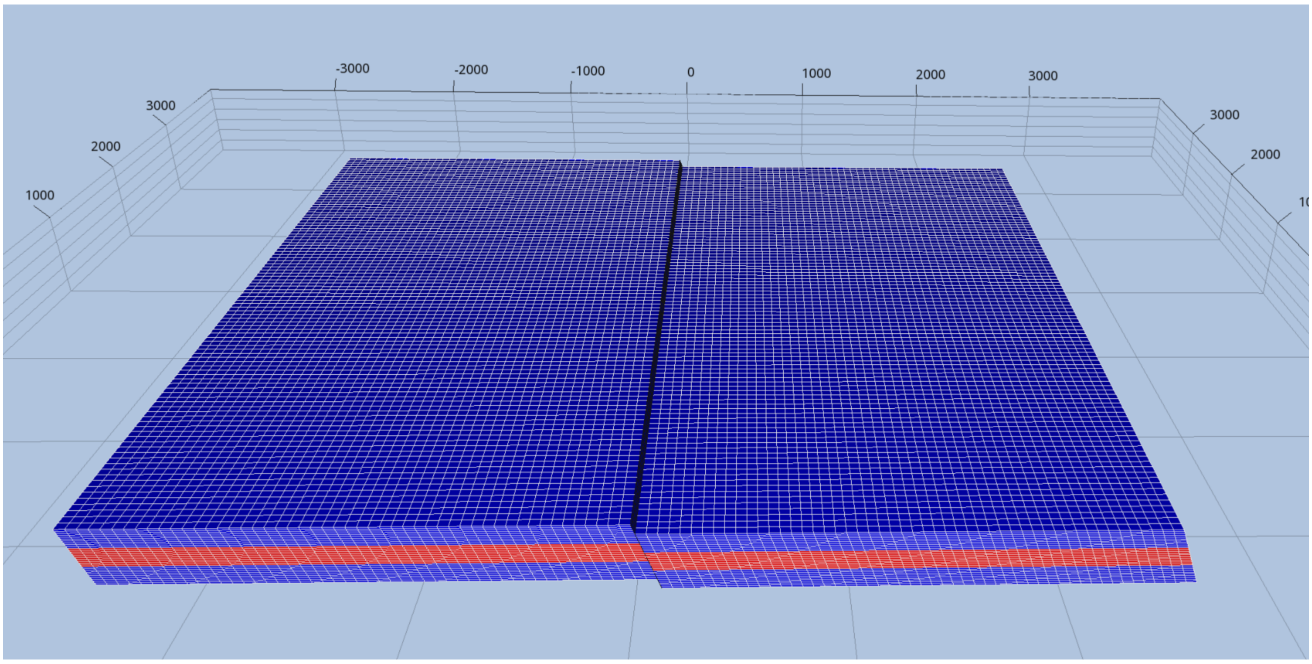

Figure 3: Case 1 Simulation Grid. The Red Layer Denotes the 100 M thick Geothermal Reservoir, the Blue Overburden and Underburden are Included for Realistic Thermal Simulation Results.

3. RESULTS

The cases consider 50 years of fluid circulation, producing 80 °C water from the producer well and reinjecting at 30 °C in the injector well. The wells are set at a flow rate of 300 m3/h, running continuously for 50 years.

Case 1:

The results are shown for the doublet after 50 years of operation (Figure 4). The changes in the pore pressure field are rather small, with almost no pressure disturbance at the fault. However, the temperature effects are significant, resulting in a large stress effect on the fault large Coulomb stress change (>>1MPa) start to develop ca. 20 years after the onset of production, when he cooling front hits the fault.

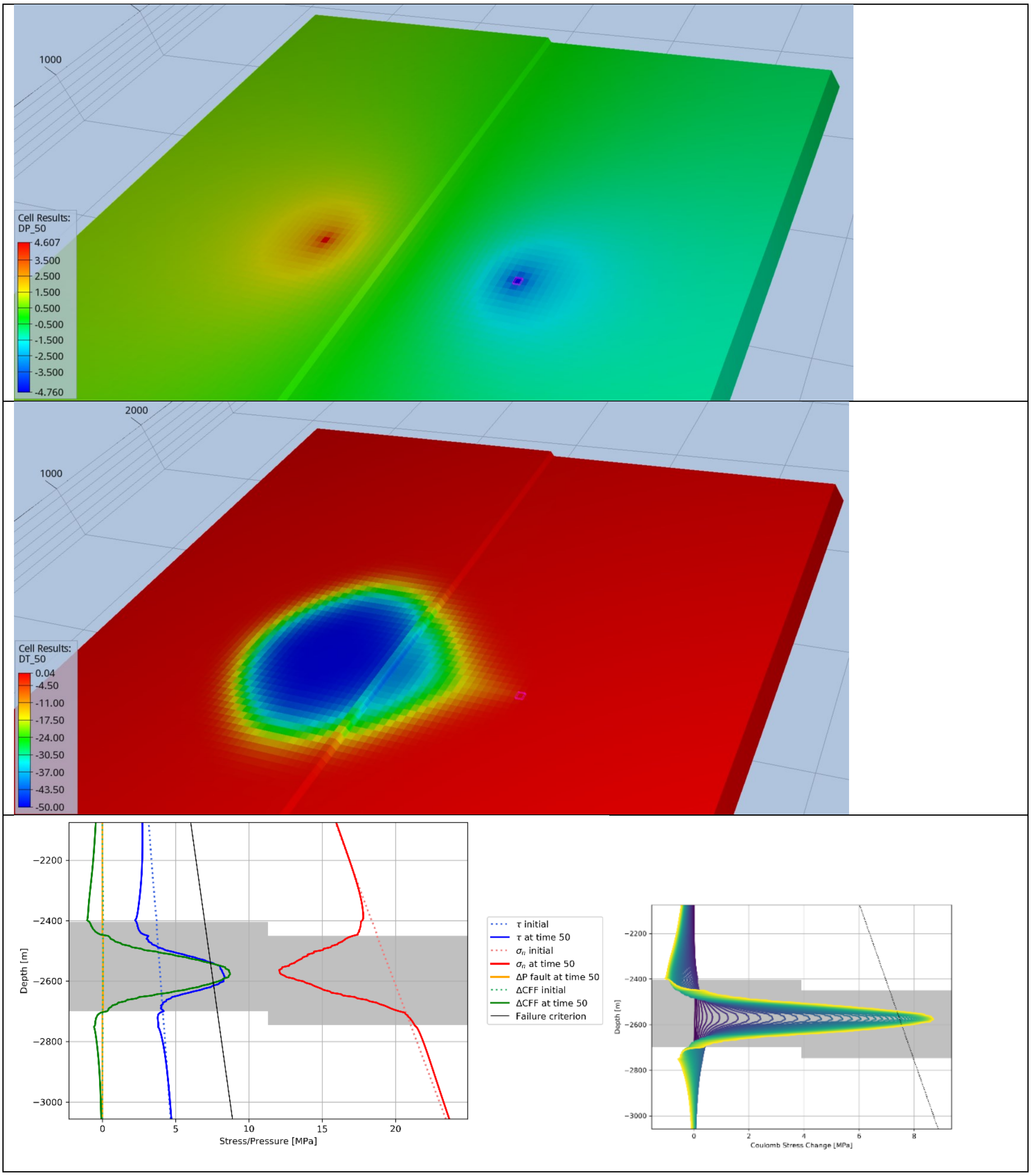

Figure 4: Case 1: Modelling of Long Term Stress Effects after 50 years of Direct Heat Production of 100 M thick Geothermal Aquifer at Ca 2500 M Depth With Fault Throw as Shown in Figure 3. Marked by Injection Temperature 30 °C and Ambient Reservoir Temperature of 80 °C. (Top) Pressure Change with Respect to Pre-operation Pressures , (Middle) Temperature Change with Respect to Pre-operation Temperature at The Middle of the Reservoir Layer and (Bottom) Stress Response at 50 years and Coulomb Stress Change at yearly Intervals at the Fault Pillar Located Closest to the Injector and Producer Well.

Case 2:

The results for the reservoir with no fault offset after 50 years of continuous operation are shown in Figure 5. As for case 1, the temperature effects are significant, resulting in approximately the same stress effect on the fault. Similar to case 1, large stresses start to develop at the fault ca. 20 years after the onset of production.

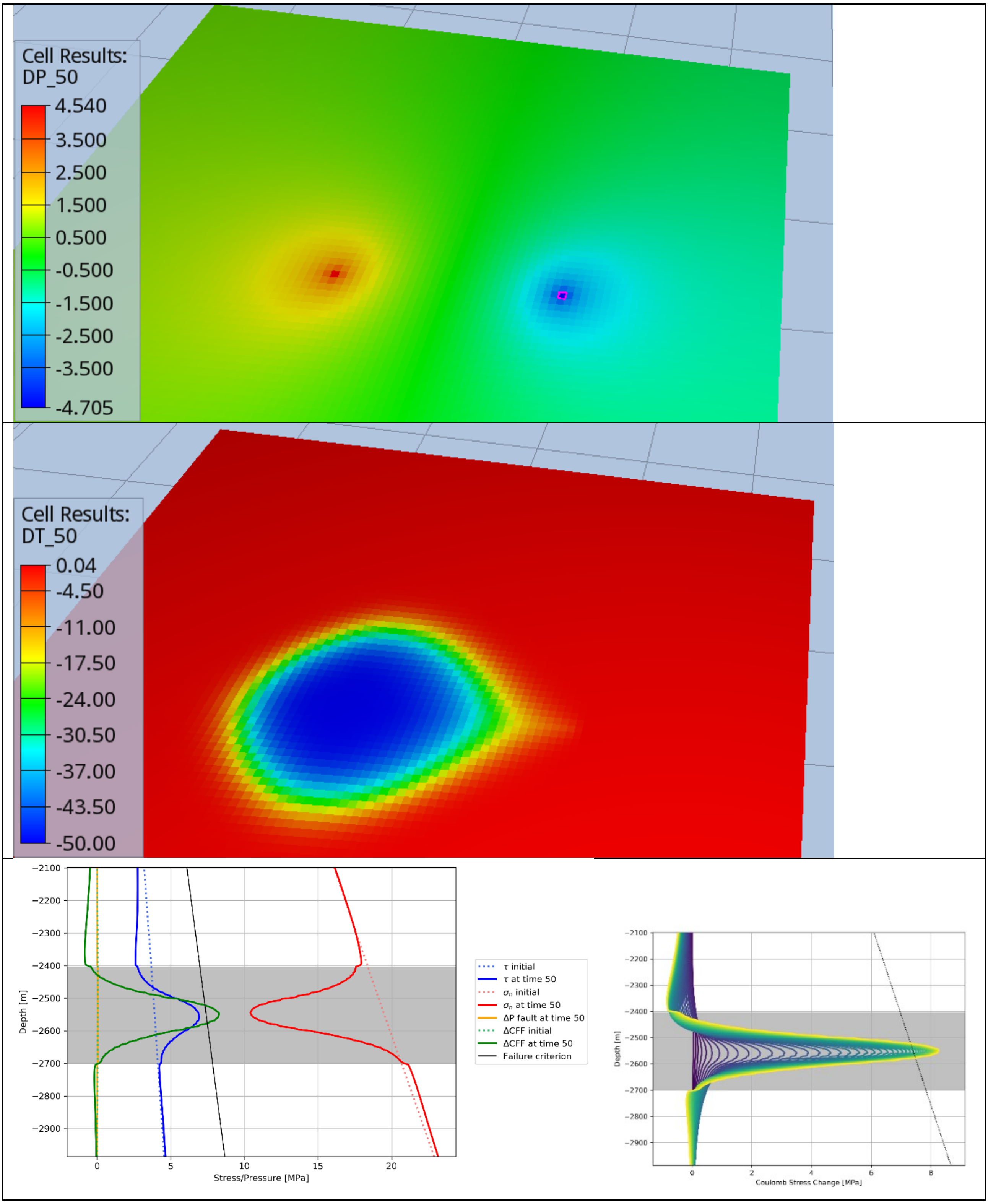

Figure 5: Case 2: Modelling of Long Term Stress Effects after 50 years Of Direct Heat Production of 100 M thick Geothermal Aquifer with No Throw on the Fault with Uniform Flow Properties at Ca 2500 M Depth. Marked by Injection Temperature 30 °C and Ambient Reservoir Temperature of 80 °C. Same Figure Conventions as in Figure 4.

Case 3:

The results for the reservoir with fault offset equal to reservoir thickness and with a well layout parallel to the fault after 50 years of continuous operation are shown in Figure 6. Compared to Case 1 and 2, the temperature effects are less significant on the fault. Similar to Case 1 and 2, large stresses result at the fault after ca. 20 years of continuous operation.

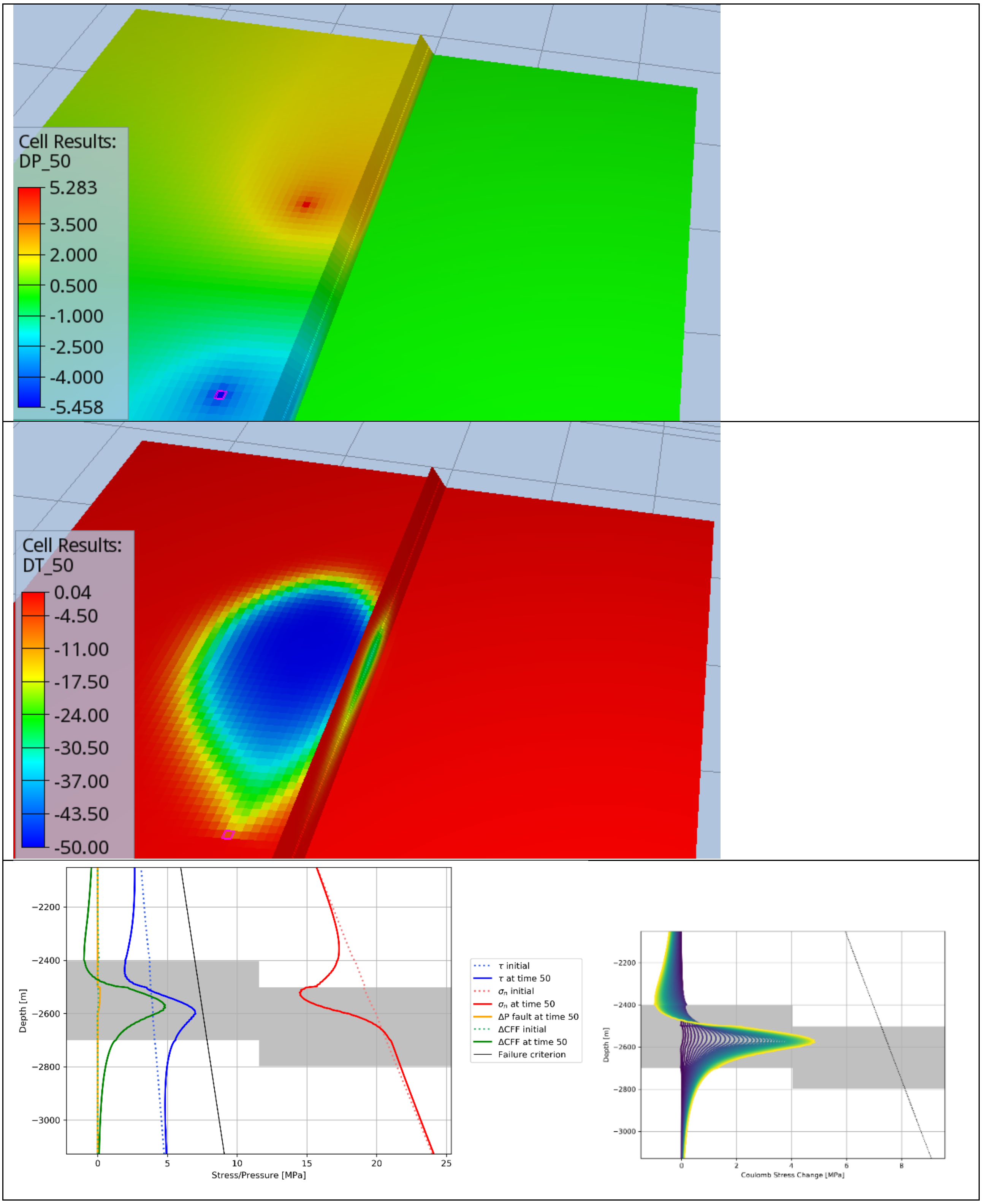

Figure 6: Case 3: Modelling of Long Term Stress Effects after 50 years of Direct Heat Production of 100 M thick Geothermal Aquifer with Throw on the Fault of 100 M. Marked by Injection Temperature 30 °C and Ambient Reservoir Temperature of 80 °C. Same Figure Conventions as in Figure 4.

3.1 Probabilistic Hazard Assessment

The predicted thermal stress response, which has a dominant effect in the Coulomb stress change on faults, scales linearly with ΔT and depends strongly on the adopted rock properties. It further scales linearly with the thermal expansion coefficient affecting predicted strains (eq. 1). In addition, the stress response as a function of the thermal strain scales linearly with the Young's modulus of the reservoir. We adopted a Young's modulus corresponding to a relatively competent rock, in agreement with the high end of the spectrum observed in core plug measurements in the Rotliegend reservoirs (NAM, 2016), which is geologically the oldest clastic reservoir used for geothermal energy production in the Netherlands. The predicted Coulomb stress changes would be up to 5 times lower for the lower range of Young's modulus values derived from core-plugs.

In a Mohr-Coulomb framework, the Coulomb stress change will not result in slip or rupture if the failure criterion is not exceeded. For the adopted fault configuration and in-situ stress conditions chosen in the models, marked by $K0_{ef}$=0.6 (Table 1), the predicted Coulomb stress changes result in a late response of slip which can result in seismic events. Figure 7 shows the seismic moment release and magnitudes if all the possible slip would be released in a single event, as a function of variability of in-situ stress (cf Van Wees et al., 2019) by adopting a range for $K0_{ef}$=0.55-0.65. Alternatively the MACRIS stress response could be used as input to predictive models for seismic events based on excitation of natural event rates (e.g. Candela et al., 2019)

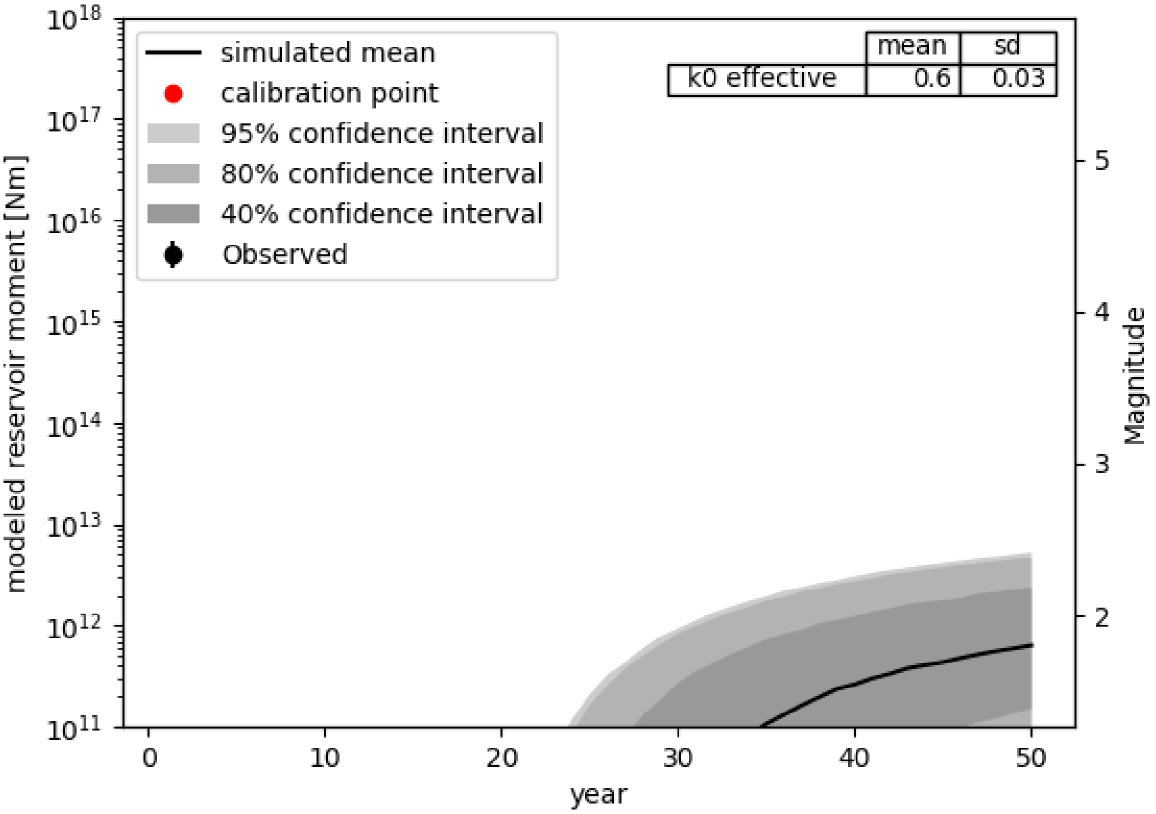

Figure 7: For case 1, predicted evolution of slip for probabilistic variation of the in-situ stress level in a range of k0=0.55-0.65 for an ensemble of 100 realisations of stress and slip response . As a consequence, the maximum expected possible slip could amount to a magnitude M=2.4 event if all slip would be released in a single event and in case of unfavourable in-situ stress conditions (cf Van Wees et al., 2019).

4. DISCUSSION AND CONCLUSIONS

The three presented cases show a significant thermal stress effect for long term operation of doublet systems. The modelled stress response at faults arrives in the modelled cases with the cold front, which can be relatively late after more than 10 years of operation if the fault prone to seismicity is located at some distance from the injector well. Whether the fault will be able to slip (and possibly rupture) upon arrival of the cold front depends on the starting in-situ stress situation and on the frictional properties of the fault system. In particular doublets drilled in competent rock types (e.g. low porosity and well consolidated marked by relatively high Young's modulus), and reservoirs marked by large temperature contrasts, may be prone to the build-up of significant thermal stresses over time (>>1MPa). The numerical predictions align well with first order estimates of stress response from adopting uniaxial thermal compaction, as the predicted ΔCFF of case 1 and 2 agrees well with the analytical solution described in section 2, amounting to 8.6 MPa.

The fact that thermal stresses can be significant, also agrees with earlier findings for the importance of thermal stress changes associated with injection (e.g. Candela et al., 2018).

Results for the homogeneous porous sandstone reservoir show that during operation, thermal stressing causes a significant increase of Coulomb stresses and can have a destabilizing effect on fault stability within the vicinity of the geothermal doublets. Increased pore pressures can cause additional positive Coulomb stressing of the faults; however, the effect of pore pressure is limited in areal extent and relatively small compared to the effect of thermal stresses, except in the first years of operation. As the cold front moves away from the injector, the fault starts to be progressively stressed relatively late after the start of production (cf Figure 7), and gradually the area of the fault exposed to destabilizing stresses gets enlarged. The effect of fault throw in the simulation appears to play a minor role in the stress response. A sealing fault is subject to a lower thermal stress compared to non-sealing faults as the thermal cooling is less pervasive in the fault zone for a sealing fault (e.g. case 3 compared to the other cases).

ACKNOWLEDGEMENTS

This work includes part of a project that received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 691728. The content of this paper reflects only the authors' view. The Innovation and Networks Executive Agency (INEA) is not responsible for any use that may be made of the information it contains.

REFERENCES

Candela, T., Van der Veer, E., and Fokker, 2018. On the Importance of Thermo-elastic Stressing in Injection-Induced Earthquakes. Rock Mechanics and Rock Engineering, pp 3925–3936.

Candela, T.,et al., 2019. Depletion-induced seismicity at the Groningen gas field: Coulomb rate-and-state models including differential compaction effect. Journal of Geophysical Research (in press). DOI: 10.1029/2018JB016670.

Kahrobaei, S. et al., 2019. Regional scale geothermal field development optimization under geological uncertainties. European Geothermal congress, extended abstract.

NAM, 2016. Technical addendum to the winningsplan Groningen Field. april 2016. www.nam.nl

Okada, Y., 1992. Internal deformation due to shear and tensile faults in a half-space, *Bulletin of the Seismological Society of America,* 82, 1018.

Stichting Platform Geothermie et al, 2018, Masterplan Aardwarmte in Nederland,

Van Wees, J.D. *et al.* , 2012. Geothermal aquifer performance assessment for direct heat production–Methodology and application to Rotliegend aquifers, *Netherlands Journal of Geosciences,* 91, 651-665.

van Wees, J.D. *et al.*, 2017. Unlocking Geothermal Energy from Mature Oil and Gas Basins: A Success Story from the Netherlands, *in Perspectives for Geothermal Energy in Europe*, pp. 187-214,

Van Wees et al., 2019. 3D Mechanical Analysis of Complex Reservoirs: a novel mesh-free approach, Geophysical Journal International (in press)