A sensitivity analysis of stress changes related to geothermal direct heat production in clastic reservoirs and potential for fault reactivation and seismicity

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Introduction

In the Netherlands, geothermal energy is considered an important future heat source, the aim is to accelerate and upscale its development by development of hundreds of geothermal doublet systems by 2050 for sustainable heating in the built environment (Stichting Platform Geothermie et al., 2018, Van Wees et al., 2020). For safe and effective application of geothermal energy, assessment of the effects of long-term cooling on reactivation and seismicity potential of faults near a geothermal doublet are required. Geomechanical models allow for understanding and evaluation of the influence and sensitivity to key subsurface processes, geological properties and operational settings affecting fault reactivation and seismic hazard.

This work presents the preliminary results of a detailed analysis of the sensitivity for fault reactivation and induced seismicity in a three-dimensional framework, taking into account both the spatial and temporal evolution of the cold-water front in the vicinity of the geothermal doublet.

Model

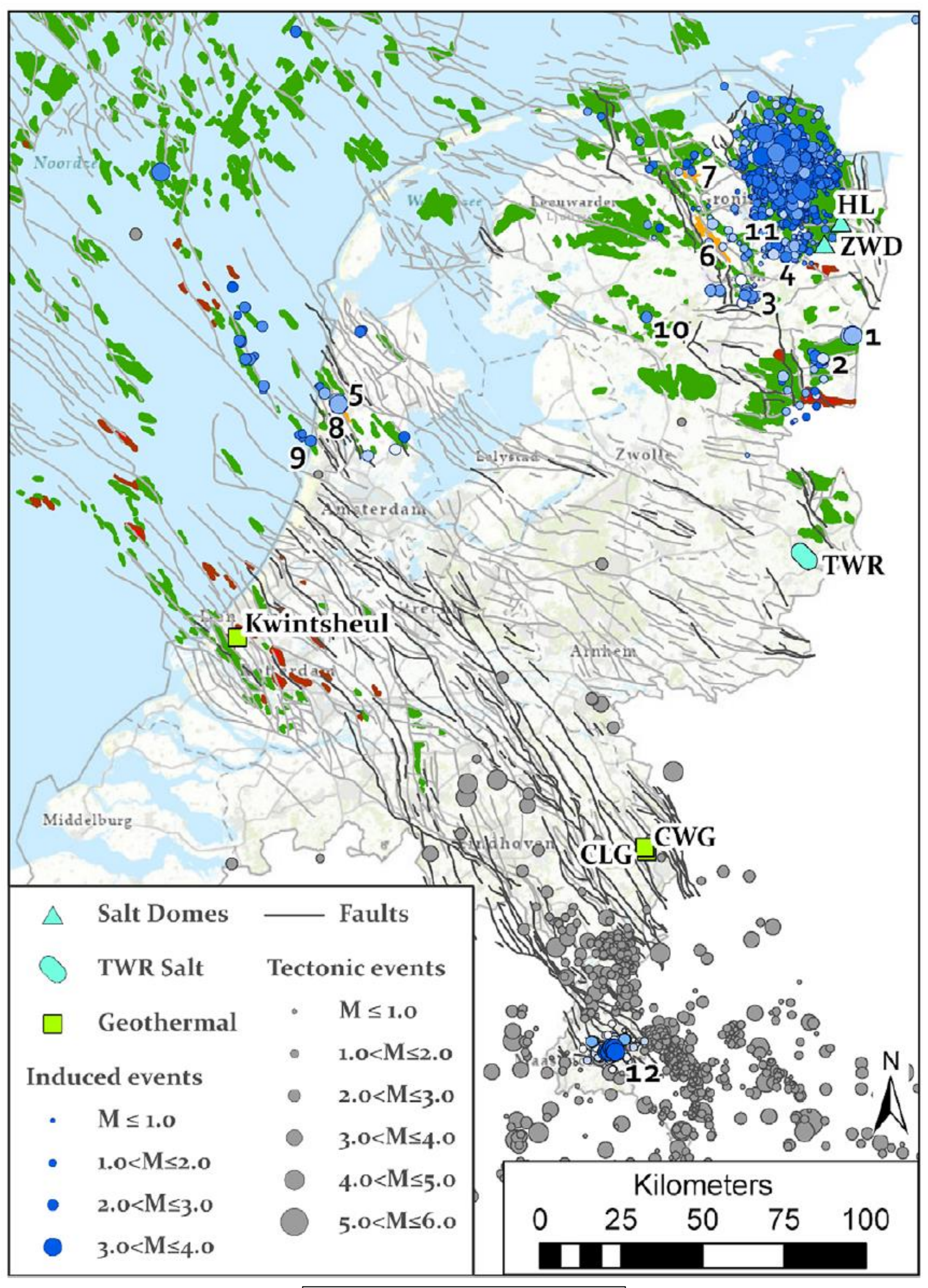
Two three-dimensional model scenarios for a geothermal doublet are considered with a fault in between the injector and producer well, **Model 1** without fault offset, the **Model 2** with a normal offset of half the reservoir thickness, and their results are compared. The 3D stress and seismicity potential analysis is performed based on an uniaxial stress solution compared to MACRIS (Mechanical Analysis of Complex Reservoir for Induced Seismicity). MACRIS is a TNO-proprietary tool that allows for poro- and thermo-elastic stress evolution in complex reservoir models (van Wees et al., 2019). In both approaches the stress changes are calculated based on finite volume changes ΔV, related to pressure and temperature changes in the reservoir:

$$\Delta V = (\, \varepsilon_{Tz} + \varepsilon_{Pz}\,)\, dV, \qquad \varepsilon_{Tz}(t) = \Delta T(t)\alpha \frac{(1+\nu)}{(1-\nu)}, \qquad \varepsilon_{Pz}(t) = \Delta P(t) \frac{(1-\nu-2\nu^2)}{(1-\nu)E}$$

In the uniaxial stress solution, the effective stress changes follows directly from the change in pressure and temperature as (Fjaer et al., 2008; van Wees et al., 2014):

$$\Delta\sigma_v'(t) = -\Delta P(t), \qquad \Delta\sigma_{hH}'(t) = \Delta\sigma_{Hh}'(t) = (\varepsilon_{Tz}(t) + \varepsilon_{Pz}(t))\frac{E}{(1+\nu)} - \Delta P(t)$$

In both models in-situ stress, thermo-mechanical, and frictional **parameters** are varied to study the sensitivity of induced stresses. **Potential magnitudes** are determined from the induced stresses. Preliminary results show the potential for fault reactivation to be predominantly affected by the thermo-elastic reservoir parameters. In addition, the intersection area of the cold-water volume in direct contact with the fault plane is shown to be the main driver for fault reactivation.



From Muntendam-Bos et al., 2021

Parameter	Symbol	Unit	Default (range)
Fault dip	θ	$^\circ$	$70\ (cte)$
Vertical stress gradient	$\Delta\sigma_v/\Delta z$	MPa/km	$22.4\ (20.4-25.5)$
Effective stress ratio σ_h/σ_v	$k_{0,eff}$	$-$	$0.51\ (0.4-0.8)$
Horizontal stress ratio	σ_H/σ_h	$-$	$0.9\ (0.5-1)$
Hydrostatic gradient	$\Delta\sigma_v/\Delta z$	MPa/km	$10.52\ (10-10.8)$
Linear thermal expansion coefficient	α	$^\circ C^{-1}$	$1e^{-5}\ (0.5e^{-5}-2.5e^{-5})$
Biot coefficient	β	$-$	$1\ (cte)$
Poisson ratio	ν	$-$	$0.2\ (0.05-0.35)$
Young's modulus	E	GPa	$15\ (5-25)$
Friction angle	ϕ	$^\circ$	$31\ (27-35)$
Friction angle drop	ϕ_{drop}	$^\circ$	$5\ (0-15)$
Cohesion	C	MPa	$0.8\ (0-4)$
Permeability	k	mD	500
Rock thermal conductivity	K_r	$W/m.K$	3
Rock specific heat capacity	c_r	$J/kg.K$	850
Initial reservoir temperature	$T_{initial}$	$^\circ C$	$81.3\ (cte)$
Injection temperature	T_{inj}	$^\circ C$	$30\ (20-50)$

Please be aware that the (variations in) parameter values are chosen such that induced events will occur. Only in this way can the sensitivity for fault reactivation and induced seismicity be investigated.

Seismic magnitude prediction

The potential cumulative seismic moment is determined from the elastic stress solution as proposed by van Wees et al. (2018), which states that the seismic moment density $M0_m\ [N]$ of the fault per unit length of strike becomes

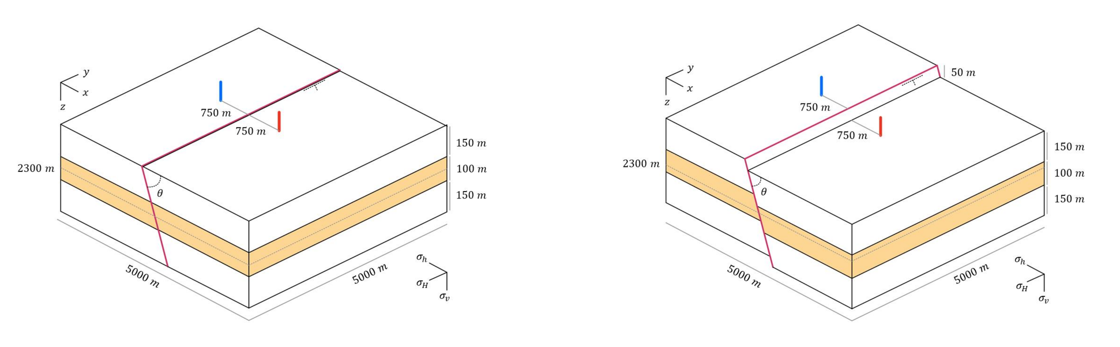
$$M0_m = \Delta\sigma \frac{l^2}{\sqrt{\pi}}$$

which applies to plane-strain dip-slip conditions in a normal faulting regime. This simplified approach discards the dynamic effects of slip and slip weakening, and assumes all incremental slip is released seismically and instantaneously. The magnitude of the seismic event can be obtained from the cumulative seismic moment CSM by (van Wees et al., 2014)

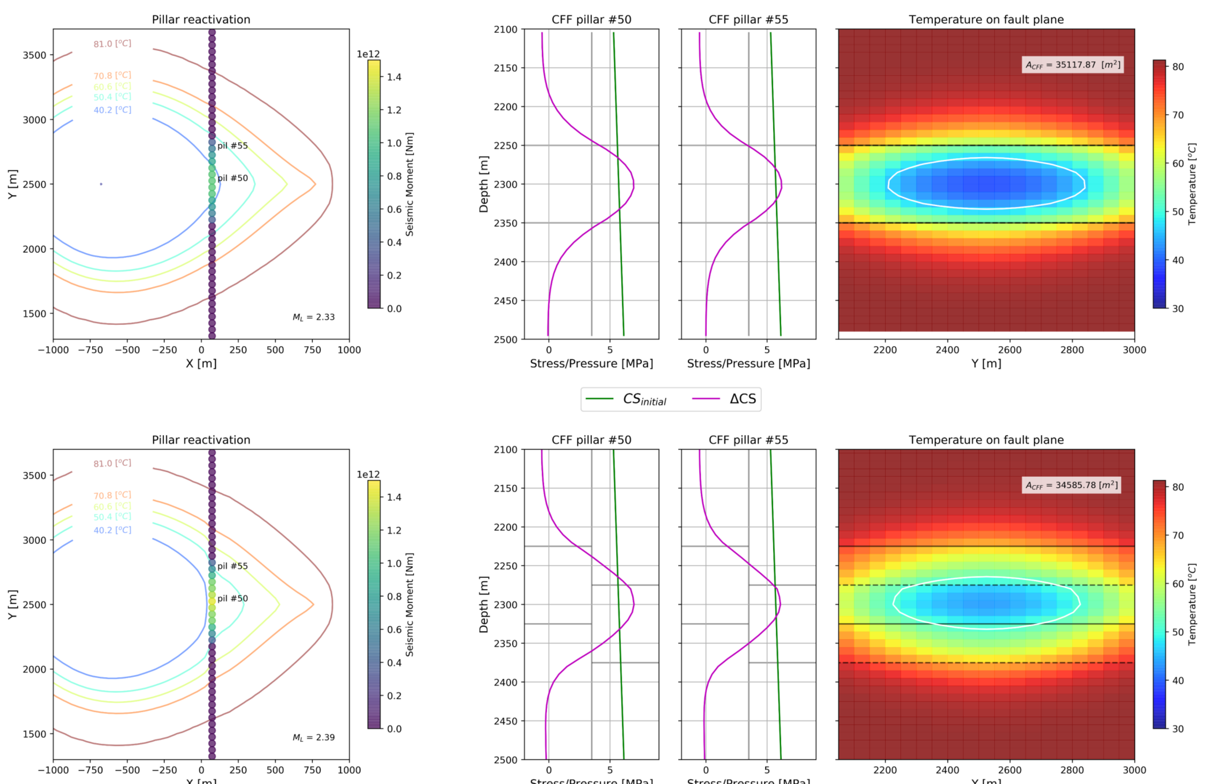
$$M_L = \frac{2}{3}\log(CSM) - 6.07$$

where CSM is the integration of the seismic moment over fault strike. Rather than assuming CSM is released in a single seismic event, CSM can be released in N events based on a Gutenberg-Richter relationship with constant b-value to provide a more realistic approach.

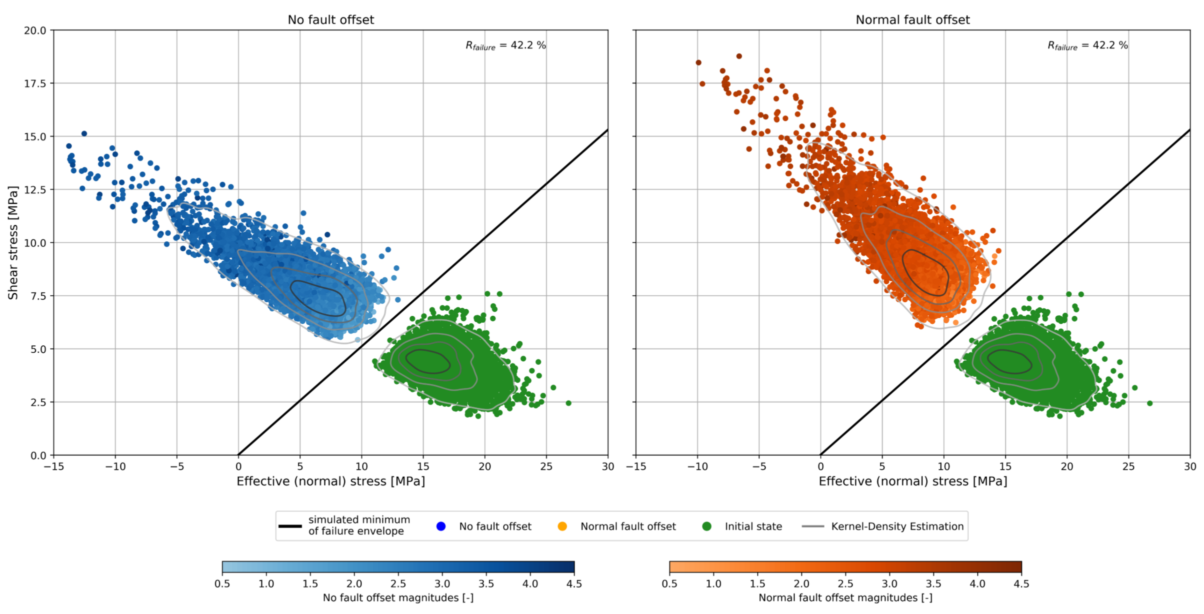
Model 1: Doublet perpendicular to fault – normal offset



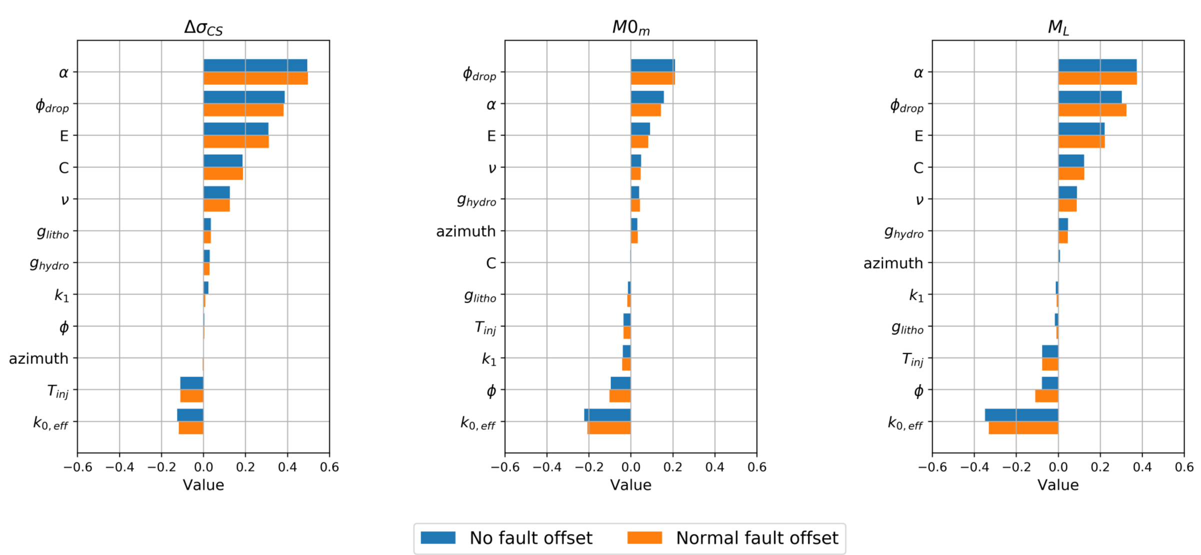
Despite the lesser degree of cooling (~8 ^oC at mid-reservoir depth) on the fault plane in the case of normal fault offset, the magnitude of the Coulomb stress changes and reactivated area A_{CFF} are similar to those of the non-offsetting fault.



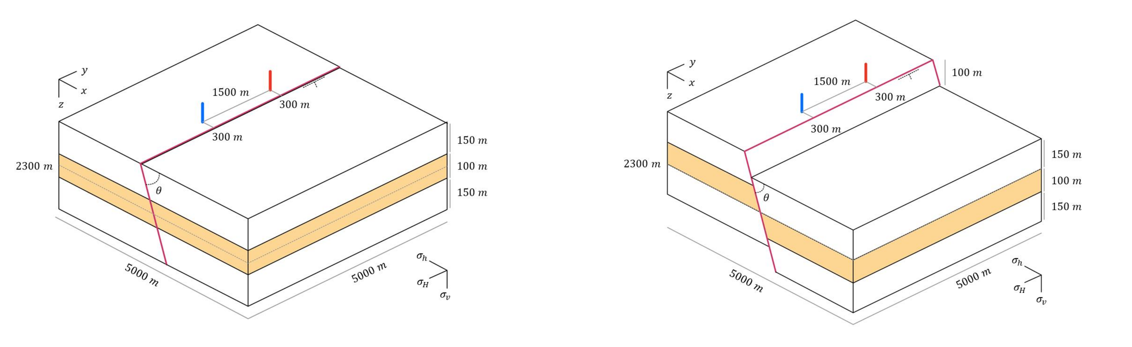
For both cases of fault offset, the ensemble of seismic hazard estimates shows that roughly 58% of the model realisations yield no fault reactivation. Those realisations in which fault reactivation does occur show a strongly destabilising stress path that is characteristic for thermo-elastic stress changes (Buijze et al., 2023).



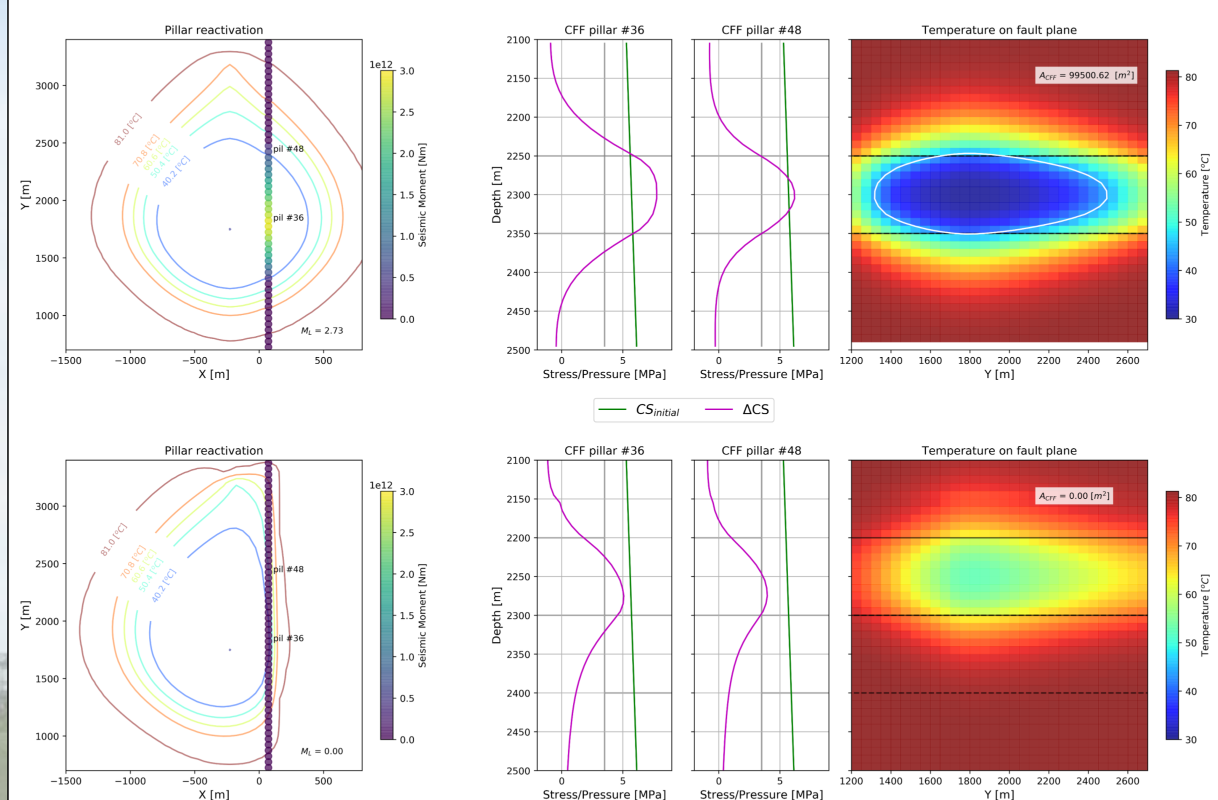
Subsurface stress changes are shown to be strongly correlated to the thermo-elastic parameters, the initial stress state and fault properties affecting slip length and resulting magnitude estimate of the seismic event. The degree of cooling is as a key operational parameter affecting fault reactivation.



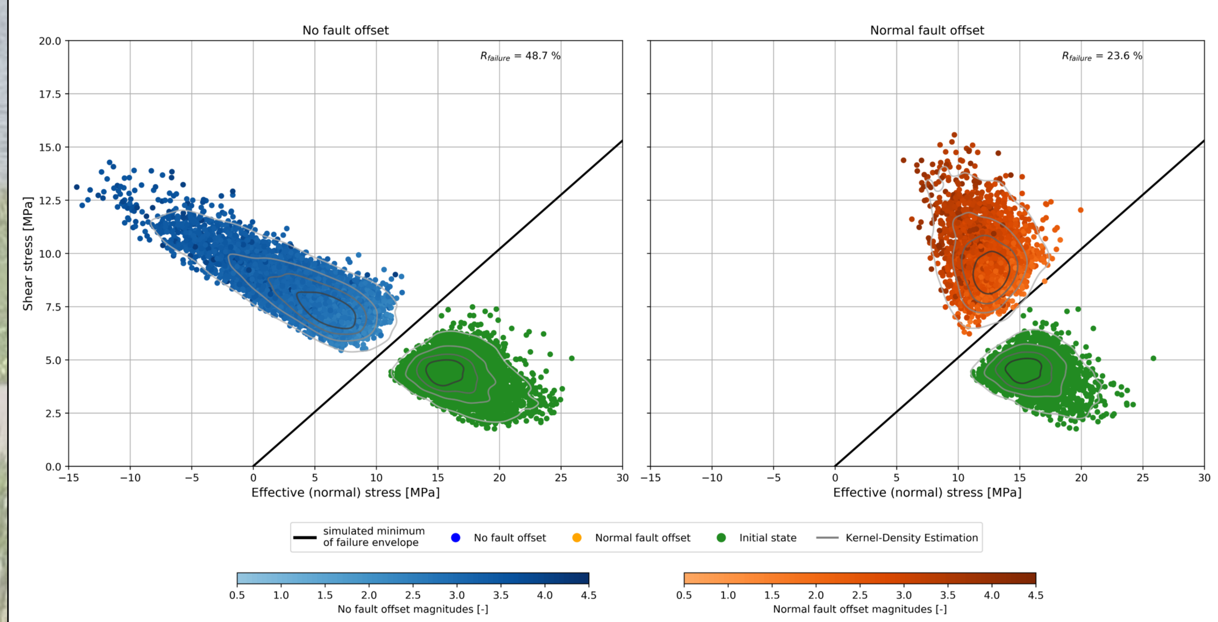
Model 2: Doublet parallel to fault – sealing fault



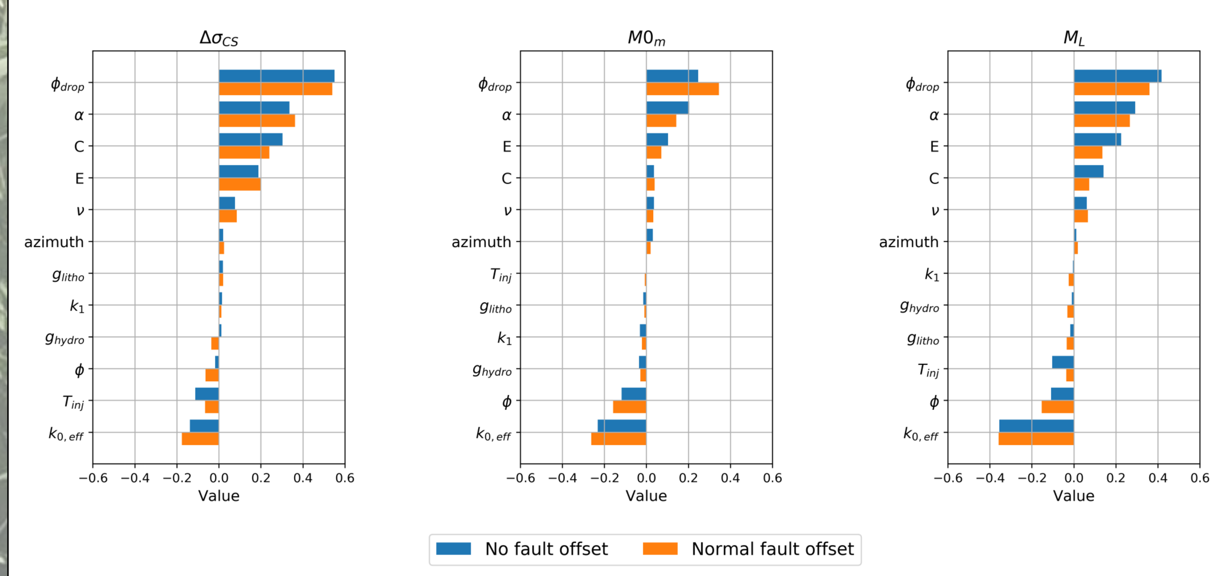
Although in direct contact with the fault plane, the cold-water volume does not intersect it, thereby effectively decreasing the degree of cooling by ~25 ^oC at the footwall reservoir depth interval and the magnitude of the Coulomb stress change.



In the case of a sealing fault, the ensemble of seismic hazard estimates shows that roughly 76% of the model realisations yield no fault reactivation. Tensile failure is absent for a hydraulically sealing fault due to 1) the lower degree of cooling on the fault plane, and 2) the significantly increased shear stress on the fault following the effects of stress arching (Marelis et al., 2023).



Subsurface stress changes are shown to be strongly correlated to the thermo-elastic parameters, the initial stress state and fault properties affecting slip length and resulting magnitude estimate of the seismic event. The degree of cooling is as a key operational parameter affecting fault reactivation.



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Conclusions

This work reports on the results obtained from a detailed analysis of the sensitivity for fault reactivation and induced seismicity considering reservoir throw, flow compartmentalization and the 3D development of the cold-water front in the vicinity of the geothermal doublet. Comparison of the model scenarios highlights the effects of stress arching and illustrates the complexity in seismic hazard estimate in the case of normal fault offset or reservoir flow compartmentalization.

The sensitivity for fault reactivation and induced seismicity can be subdivided into two categories; 1) the elastic stress changes in the subsurface leading to fault reactivation, and 2) the initial stress state and fault properties affecting slip length and resulting largest magnitude estimate of the seismic event.

The occurrence and magnitude of an induced event is shown to be strongly correlated to the initial stress state which emphasizes the need for site-specific hazard assessment. In view of the stabilizing effect of the injection temperature, the degree of cooling poses as a key operational parameter affecting fault reactivation.

The presented maximum possible seismic event magnitudes are subject to significant uncertainty, in view of the uncertainty in the chosen model parameters, including in-situ stress, mechanical and frictional properties.

Results show MACRIS to be an effective tool in seismic hazard assessment as its solution can handle structurally complex reservoirs. In conclusion, the extent to which the cold-water front intersects or is in direct contact with the fault plane, given an initial stress field, is shown to be the main driver for fault reactivation and subsequent seismic potential.

The research has been performed as part of the **WarmingUP project**. WarmingUP is a Dutch research programme under the Meerjarig Missiegedreven Innovatieprogramma (MMIP 4), funded by RVO, project number TEUE819001.

Additional details

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