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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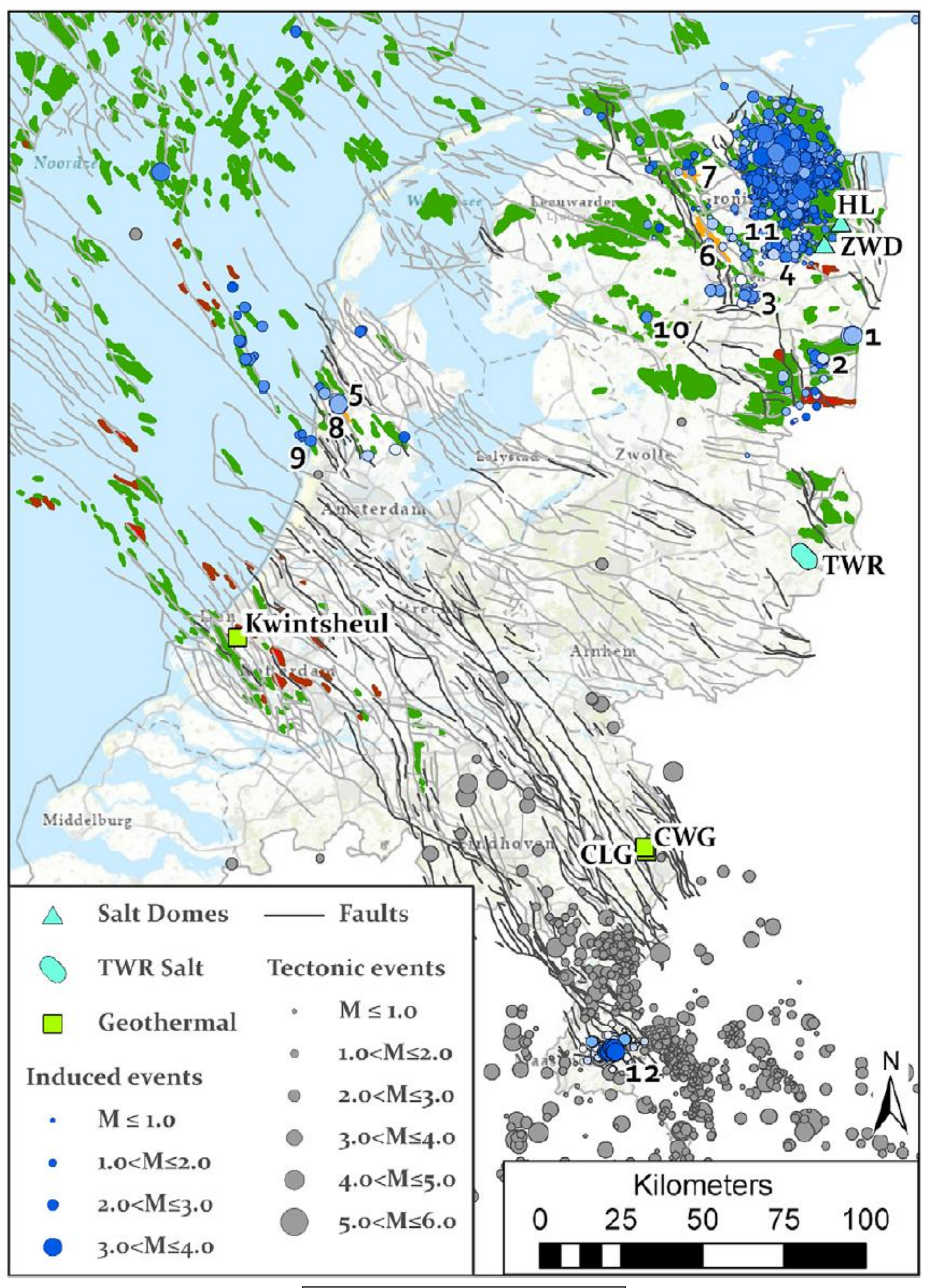
Introduction

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.



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

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:

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

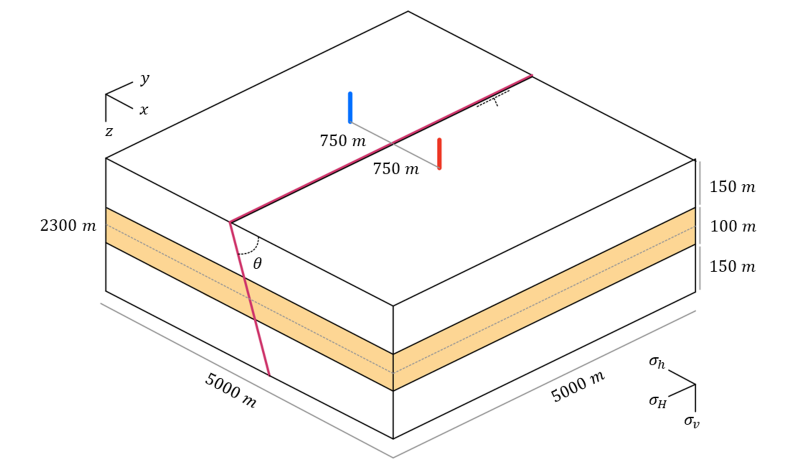
In the uniaxial stress solution, the effective stress changes follows directly from the change in pressure and temperature as (Fjaer et al., 2008; van Wees et al., 2014):

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

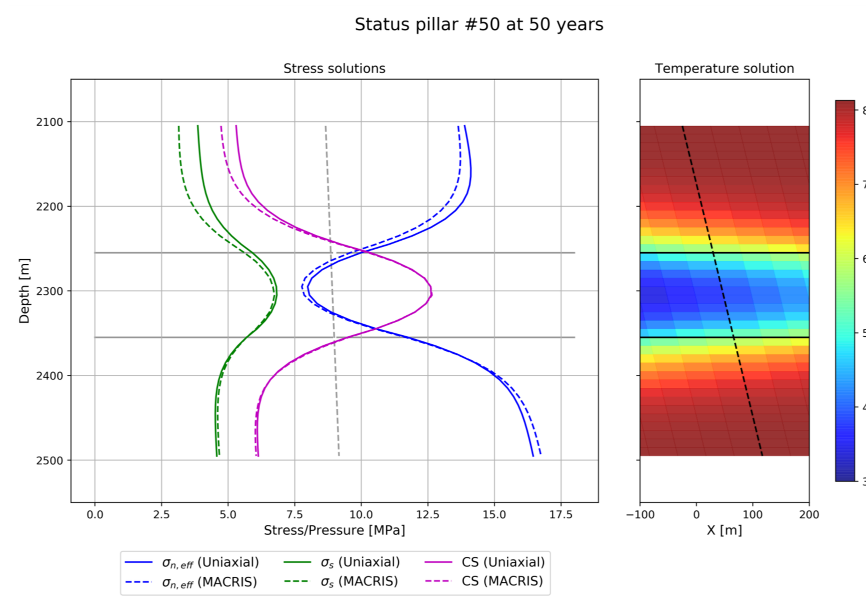
In both models in-situ stress, thermo-mechanical, and frictional **parameters** are varied to study the sensitivity of induced stresses. **Potential magnitudes** are determined from the induced stresses. Preliminary results show the potential for fault reactivation to be predominantly affected by the 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.

Model 1: No fault offset – stress and strain

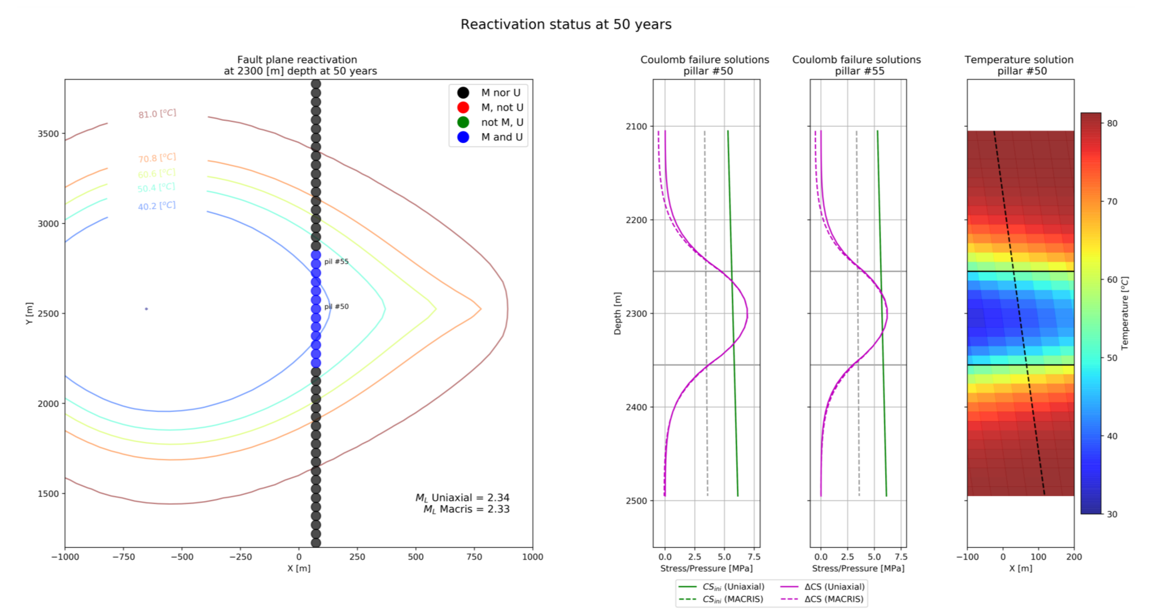
In the case the reservoir is not offset by the fault, the subsurface stress response can be approximated using an analytical approach based on uniaxial reservoir compaction. Assuming no horizontal strain and constant vertical stress results in any stress arching effects being neglected.



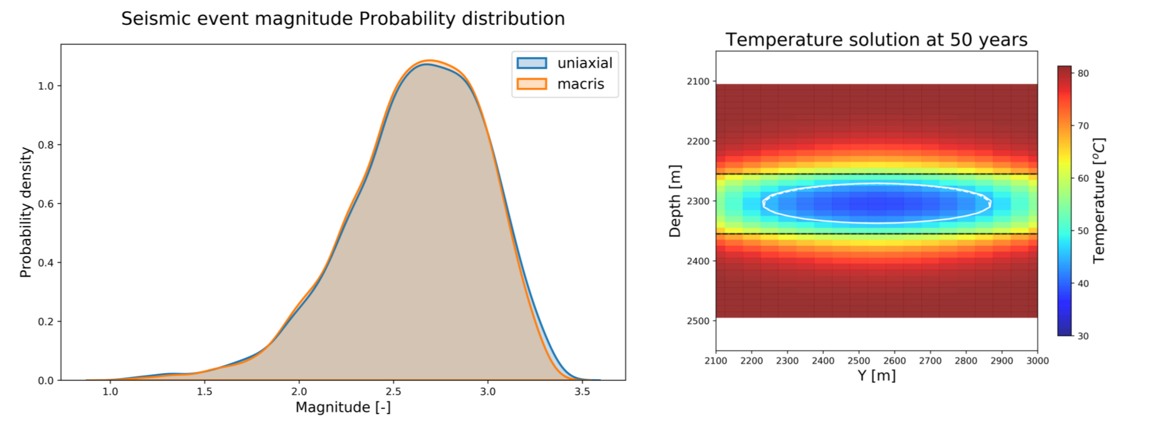
Uniaxial solution deviates less than 1% from absolute Coulomb stress peaks.



No deviation of uniaxial solution in terms of reactivated fault pillars (i.e. $CFF > 0$). Number of reactivated pillars coincides with the extent to which the thermal front laterally intersects the fault plane.

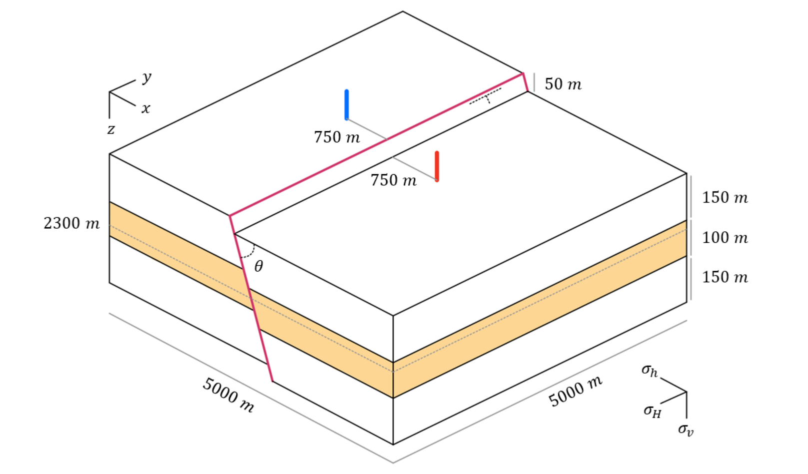


No considerable deviation of the uniaxial solution in terms of the estimation of a certain magnitude given the occurrence of an induced event.

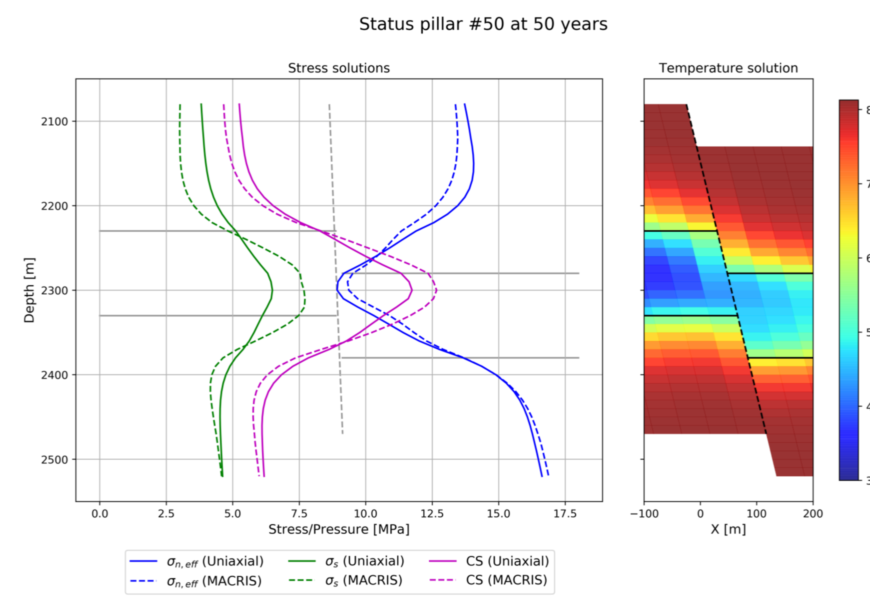


Model 2: Normal fault offset – stress and strain

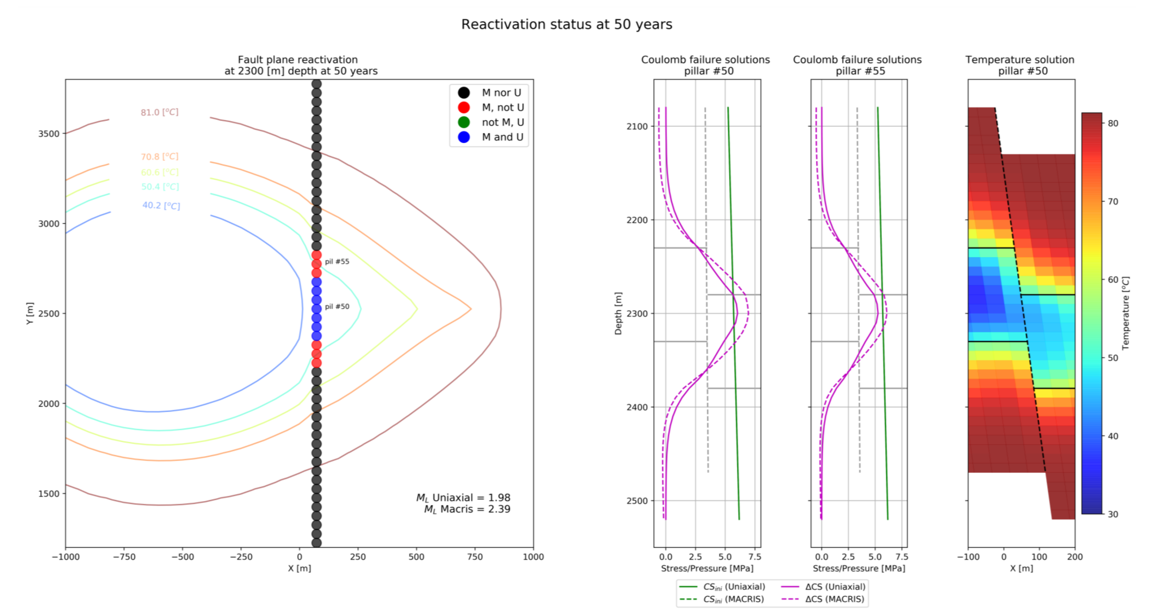
In the case the reservoir is offset by the fault, the structural complexity of the subsurface model increases and the uniaxial solution presented above is likely inadequate in the approximation of the subsurface stress response.



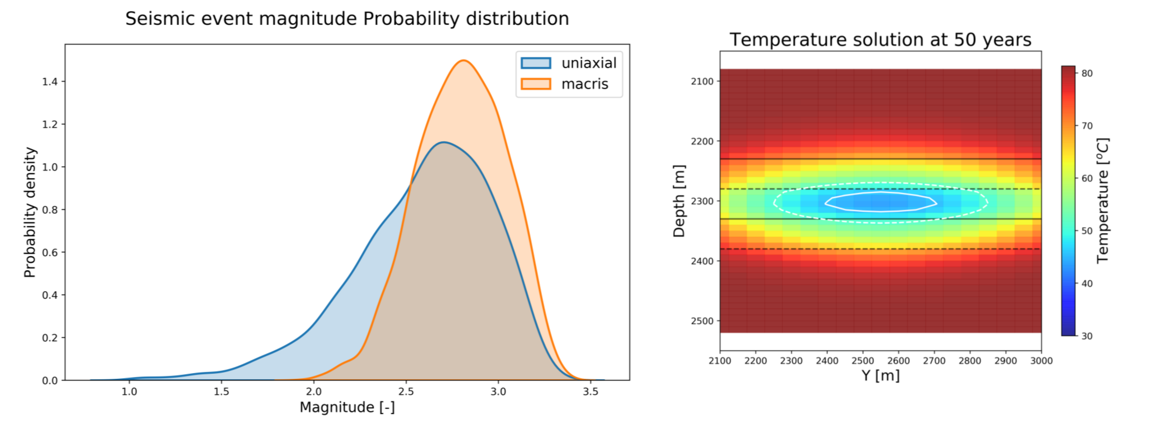
Uniaxial solution deviates less than 15% from absolute Coulomb stress peaks. Note the difference in shear stress; arching effect (Wassing et al., 2021)



Significant deviation of uniaxial solution in terms of reactivated pillars (i.e. $CFF > 0$). Including the effects of stress arching yields reactivation on outer pillars even though they show less thermal cooling. Estimated largest magnitude deviates 17% in the absence of stress arching effects.



Again, significant deviation of the uniaxial solution in terms of the estimation of a certain magnitude given the occurrence of an induced event. Not only does the estimated magnitude increase, so does the occurrence of events related to that magnitude.



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Conclusions

Comparison of both model scenarios illustrates the additional complexity in stress response when normal fault offset is introduced. It was shown that the analytical uniaxial solution serves as a good approximation for Coulomb stress and seismic hazard prediction for the cases considered. This implies that the effect of variations in mechanical parameters can be effectively determined from the equations presented above, and their effect is found to be in line with results presented in Buijze et al. (2022).

The presented maximum possible seismic event magnitudes of $M{\sim}2{,}5$ are subject to significant uncertainty, in view of the uncertainty in the chosen model parameters, including in-situ stress, mechanical and frictional properties.

Buijze et al. (2022) report wide magnitude ranges considering a comprehensive range of uncertainties, and the magnitudes obtained in this work are in close agreement with the reported range in Buijze et al. (2022).

Results show MACRIS to be an effective tool in seismic hazard assessment as its solution can handle structurally complex reservoir and is in good accordance with analytical and industry proven solutions. In conclusion, the extent to which the cold-water front intersects the fault plane within a given initial stress field is shown to be the main driver for fault reactivation and subsequent seismic potential.

Additional details

For any future questions please contact me at: a.a.marelis@uu.nl