

Trias-Westland GT: Seismic Hazard Analysis

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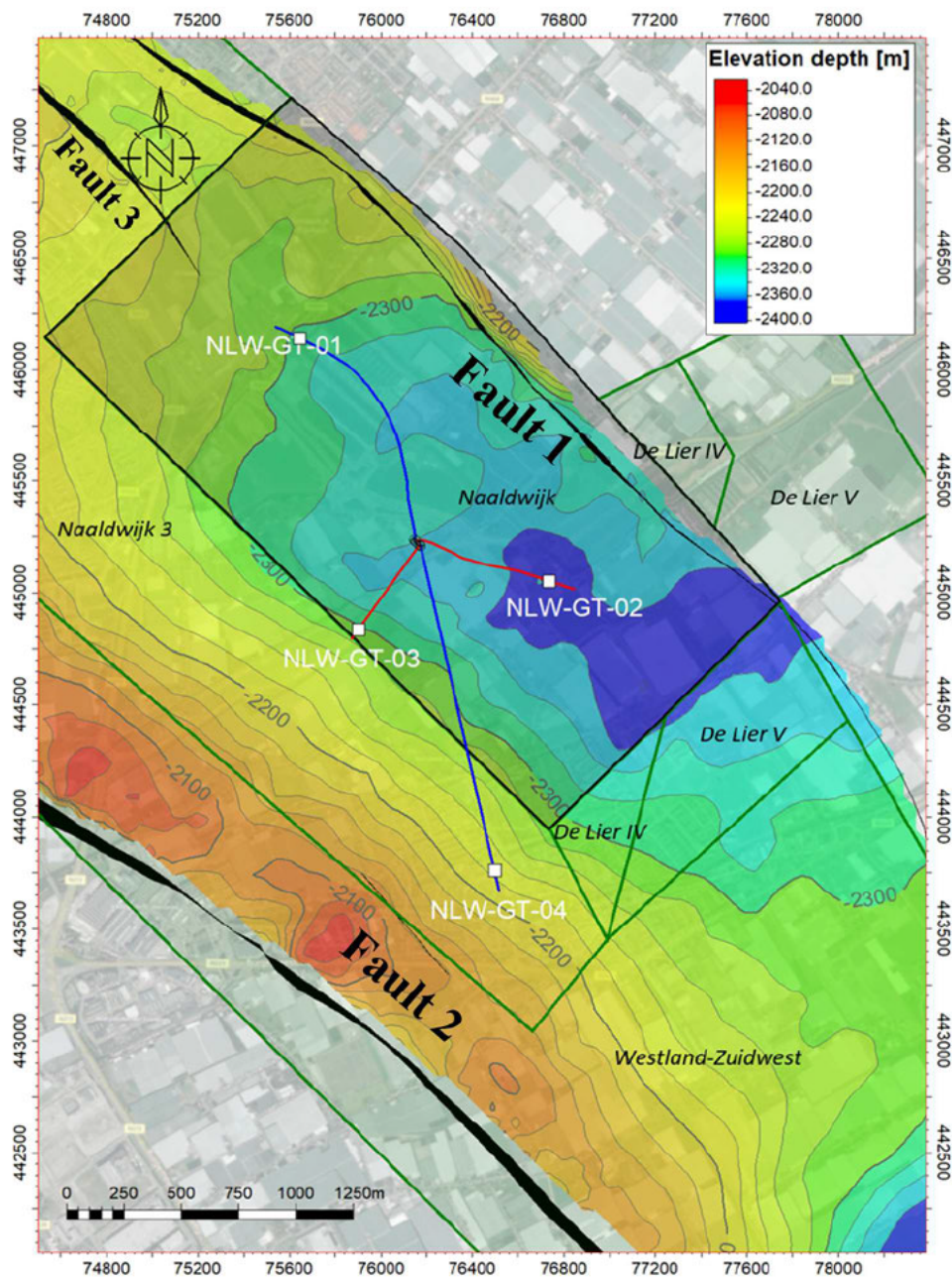
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1 Nederlandse samenvatting

Dit rapport geeft een Level-2 (locatie-specifieke) Seismic Hazard Assessment (SHA) voor het Trias-Westland aardwarmteproject van HVC. De score van de Trias-Westland II SHA Level-1 Quick-Scan (Q-CON/IF technology, 2016) werd eerder vastgesteld op 0.30 door (PanTerra, 2018). Deze score betekent dat er een laag seismisch risico is. Vanwege de oriëntatie van het spanningsveld en het feit dat het doublet wordt geplaatst in een gebied dat afgescheiden is door breuken zijn de risico's mogelijk hoger. Om de risico's grondiger te analyseren is een locatie-specifieke SHA uitgevoerd voor de geothermische operatie van Trias-Westland.



Figuur 1-1 Top Delft reservoir dieptekaart van het winningsgebied met geplande putten, penetratiepunten (witte vierkantjes) en breuklijnen (zwart, Fault 1 t/m 3).

Figuur 1-1 is een kaart van de top van het Delft reservoir – gekleurd met diepte. De meest opvallende breuken zijn de breuken 1, 2 en 3. Breuk 1 heeft een verzet van ~120 m op ~750 m van injectieput NLW-GT-01. Breuk 2 heeft een verzet van ~100 m op een afstand van ~600 m van injectieput NLW-GT-04. Breuk 3 is ~parallel aan de lijn van NLW-GT-01 naar de tip van deze breuk. Deze tip is op 800 m van NLW-GT-01 en heeft een verzet van ~30 m.

Het Trias-Westland aardwarmteproject heeft als doel om 85°C water te produceren uit de Delft zandsteen formatie en om koud water met laagst mogelijke temperatuur van 25°C terug in hetzelfde reservoir te injecteren. Wanneer het geïnjecteerde water een breuk bereikt kunnen de spanningen op die breuk veranderen en in theorie leiden tot breuk reactivatie en seismische activiteit. Of een breuk mogelijk wordt geactiveerd of niet kan berekend worden door middel van een geomechanische analyse.

Het risico op breukactivatie wordt uitgedrukt in de parameter SCU (Shear Capacity Utilisation). Bij een SCU kleiner dan 1 is breukactivatie onmogelijk. Zodra deze parameter groter wordt dan 1 bestaat een kans op breukactivatie. Echter bij een $SCU > 1$ hoeft in de praktijk geen breukactivatie op te treden. Op dit moment zijn er nog geen projecten in de operatiefase met een $SCU > 1$ waarbij breukactivatie is waargenomen.

Een relevant fenomeen in deze studie is “arching” – wat betekent dat niet-afgekoelde delen van het reservoir het gewicht van ondiepere lagen dragen. Dit effect is het sterkst wanneer de laterale extensie van het afgekoelde gebied beperkt is. “Archiving” beperkt de kans op breuk (re)activatie en het effect hiervan wordt berekend in de geomechanische modellen. Het effect van “arching” kan afnemen gedurende de levensduur van het doublet. Dit komt omdat de laterale extensie van de afgekoelde zone toeneemt naarmate er langer geïnjecteerd wordt. Hoe groter deze laterale extensie wordt, hoe minder “arching” plaatsvindt door aangrenzende niet afgekoelde reservoir zones.

De hier toegepaste workflow is recentelijk ontwikkeld door PanTerra (van den Hoek & Poessé, 2021), omdat de huidige richtlijnen van Q-CON/IF technology (2016) voor een “niveau 2” SHA geen duidelijk kader bevat hoe dit soort studies uitgevoerd moeten worden. De werkwijze bevat een geomechanische bepaling van de temperatuur van het koelere waterfront en van de thermo-mechanische effecten gedurende de termijn van de Trias-Westland geothermische operatie.

Voor dit doel zijn twee types van geomechanische modellen gebruikt:

1. Een 2-D analytisch model dat het mechanisme weergeeft van mogelijke seismische activiteit door berekening van lokale spanningsveranderingen rond een breuk als gevolg van geothermische operaties gedurende de termijn van de geothermische operatie.
2. Een 3-D Mohr-Coulomb benadering die gebruikt wordt voor probabilistische methodologie, waarbij de kans op een mogelijke seismische gebeurtenis wordt geanalyseerd.

De conclusie van deze studie is dat voor 25°C water injectie in de Delft zandsteen formatie bij een debiet van 430 m³/hr @ 80% uptime gedurende 30 jaar de kans op reactivatie van breuk 1 “laag” tot “midden” is voor doublet 1 (~10-20% > 1.0 SCU, afhankelijk van de doorlatendheid van de breuk), en de kans op reactivatie van breuk 3 “laag” (~10% > 1.0 SCU) is. Voor doublet 2 is voor 25°C water injectie in de Delft zandsteen formatie bij een debiet van 300 m³/hr @ 80% uptime gedurende 30 jaar het risico op reactivatie van breuk 2 “midden” (~20-30% > 1.0 SCU, afhankelijk van de doorlatendheid van de breuk).

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2 Introduction

2.1 Area of interest

The Trias-Westland doublets, owned by HVC, is situated in the municipality of Westland in the province Zuid-Holland. The doublets, consisting of producer NLW-GT-02 and injector NLW-GT-01 (doublet 1), and of producer NLW-GT-03 and injector NLW-GT-04 (doublet 2) are located within the Westland geothermal exploration concession (Figure 2-1). The target reservoirs are the fluvial sands of the Delft Sandstone Member, which is the main target of other doublets in this region.

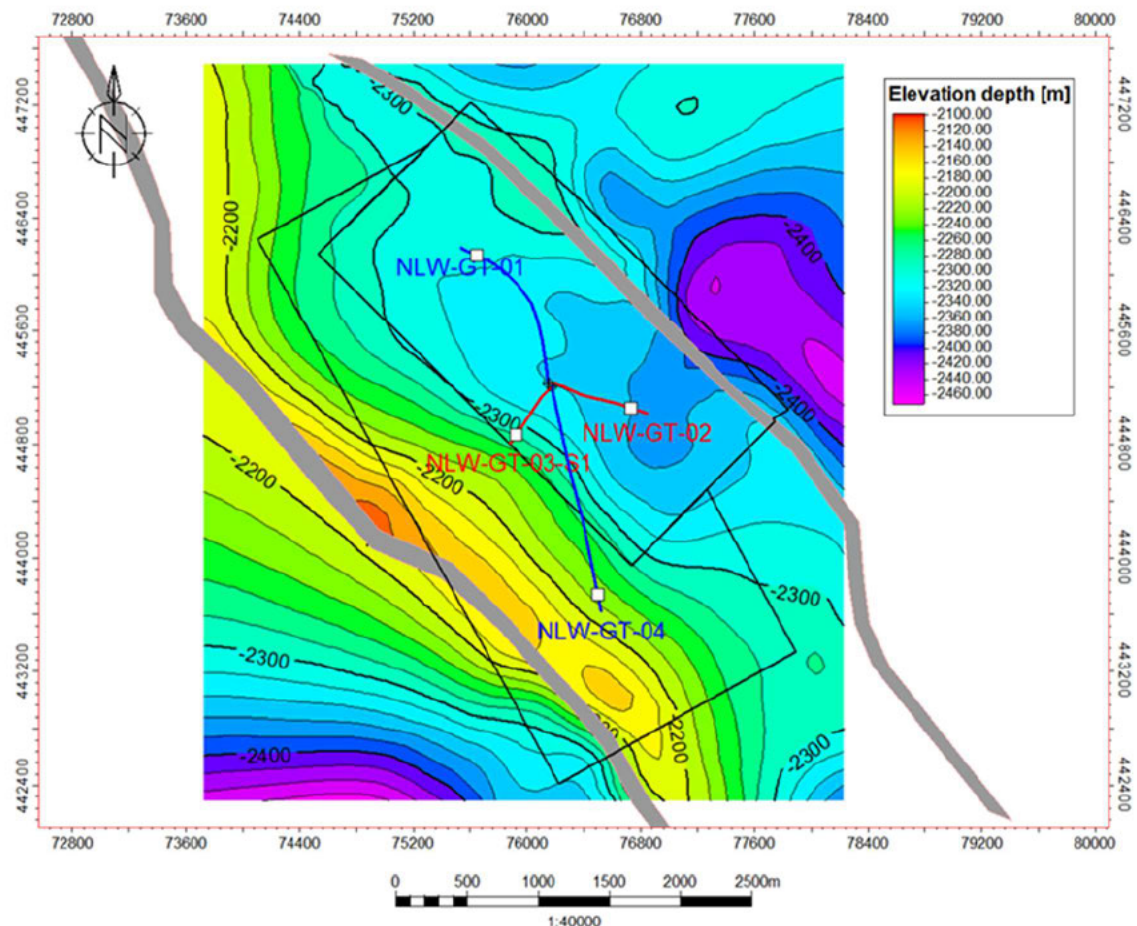


Figure 2-1 Top reservoir structural depth map with the subsurface location of the wells (white squares) with reference to the Trias Westland geothermal licences.

2.2 Guidelines for geothermal projects

A Decision tree (Figure 2-2) for carrying out a Seismic Hazard Assessment (SHA) has been made by Q-CON/IF technology (2016). This decision tree contains three risk levels, with required levels of relevant studies associated to it. In 2018, a Level 1 SHA (lowest level 'Quicksan') was carried out for Trias Westland. The resulting score from the SHA Quick-Scan was determined to be equal to 0.30 for each of the planned doublets by (PanTerra, 2018). This is associated with low seismic risk. However, due to the orientation of the stress field and the fact that the doublet will be placed in an area separated by faults, the risks can arguably be classified higher. Therefore, an independent detailed geomechanical study (location-specific seismic hazard assessment) was performed for the geothermal operation of Trias-Westland. This report touches upon the aspects that are involved in a Level 2 SHA. The current guidelines by IF/Q-CON only partially define the level-2 SHA and no clear framework exist about how to conduct such a study. For this reason a recently developed new SHA-methodology (van den Hoek & Poessé, 2021) was applied for Trias-Westland.

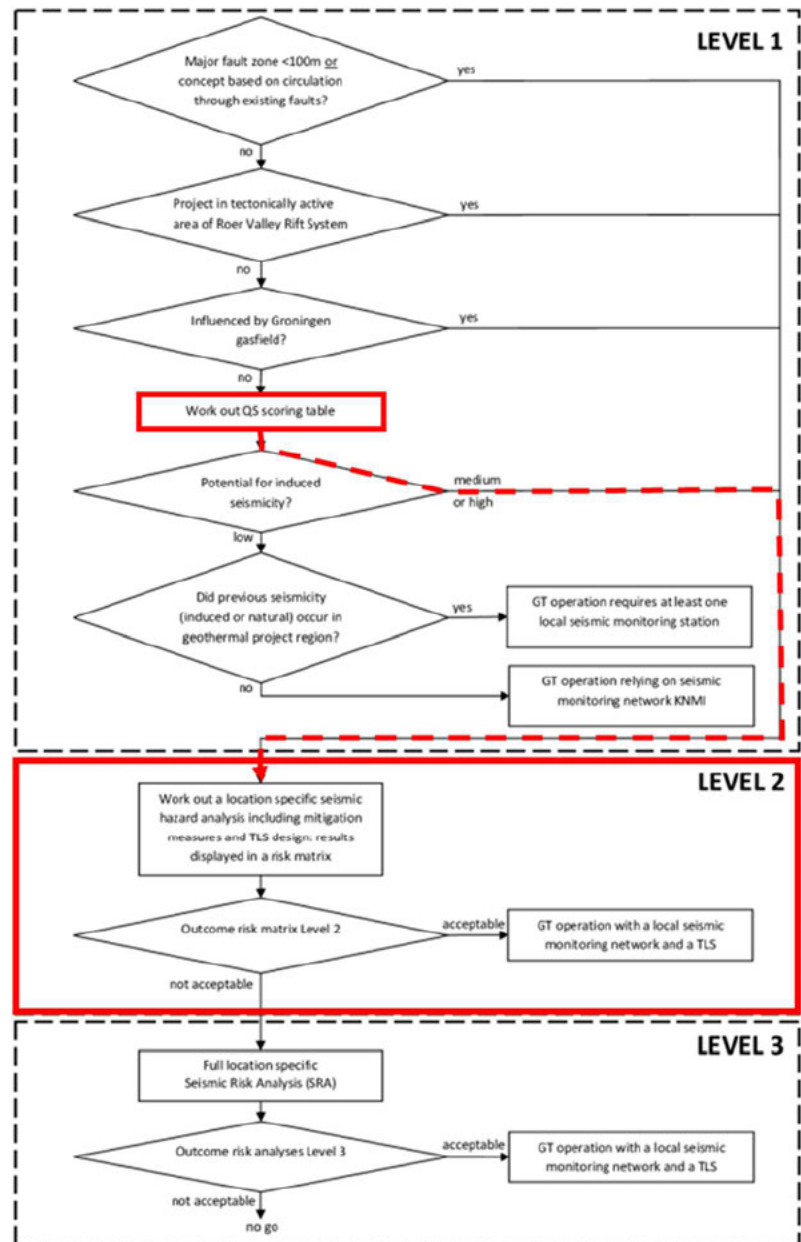


Figure 2-2 Decision tree as presented in the report by Q-CON/IF technology (2016). In this report Level 2 (red outline) is covered. TLS stands for Traffic Light System.

3 Methodology

Because currently no guidelines exist for carrying out a Level 2 Seismic Hazard Assessment (SHA), the methodology used in this study is based on the recently proposed approach by van den Hoek & Poessé (2021). Geo-mechanical models were created to understand the thermo-mechanical effects in the lifetime of the Trias-Westland geothermal operation. Van den Hoek & Poessé (2021) used an analytical analysis to carry out a detailed study of the stress changes along nearby faults as a result of geothermal operations over the lifetime of a field. In the current study, the same approach is used. The analytical model can be considered as an exact solution to the stress concentrations induced by cooling. The focus of this study is the geomechanical effects in the Delft formation. The approach to simulate the stress changes induced by cooling is presented in some more detail in paragraph 2.1 below. The 3-D Mohr-Coulomb model uses both a deterministic and a probabilistic methodology. This methodology was presented in 2020 by Poessé & van den Hoek (2020) and is summarised in section 3.2.

At the moment no seismic events or small earthquakes have been reported as a result of geothermal operations. In future, when seismic sensors detect seismic activity, the models will need to be calibrated and predictions can be updated.

3.1 Two-dimensional analytical model to simulate stress changes induced by cooling

The analytical model was developed in-house. It is based on an elaboration of the so-called Goodier integral expression for stresses induced by changes in reservoir pressure and / or temperature, see for example Koning (1988). This results in an exact solution of the induced stress changes, and therefore comparison with finite element calculations of the same geometry should give good agreement. This is indeed what was achieved in a validation study by PanTerra that was carried out as part of the in-house model development.

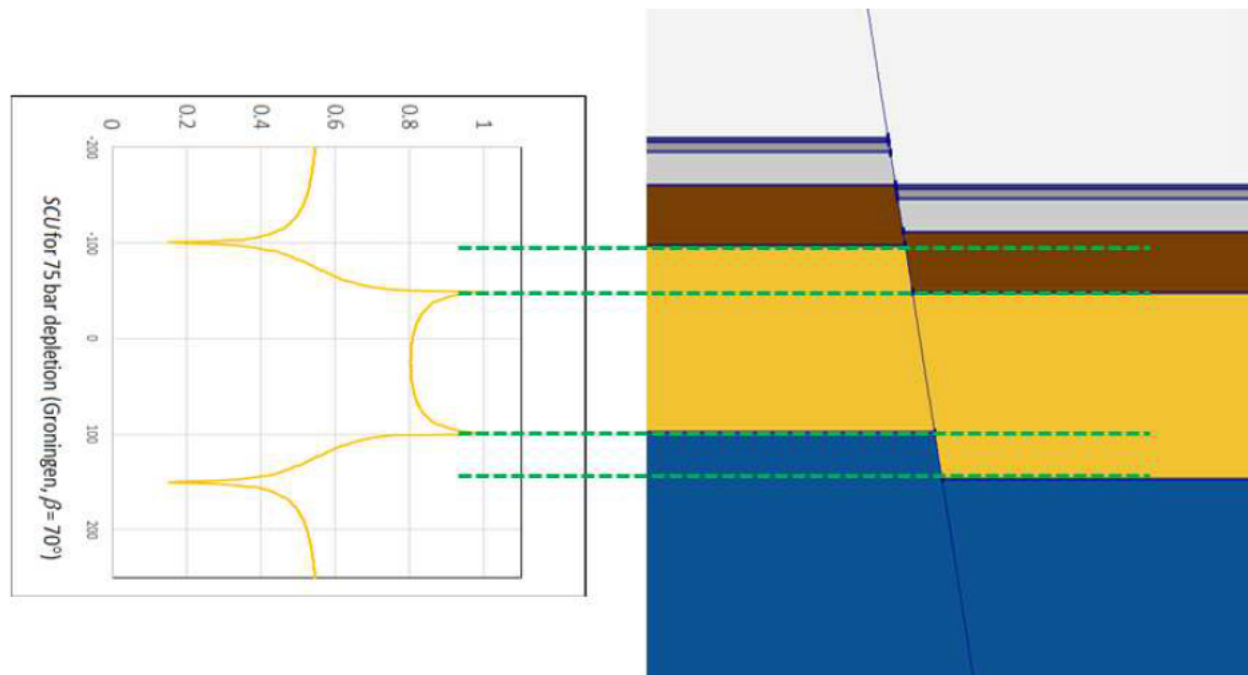


Figure 3-1 Profile of the computed “Shear Capacity Utilisation” (SCU) along the fault for a Groningen-field situation, with 75 bar reservoir depletion.

Figure 3-1 shows a typical result as computed for the example of 75 bar depletion in the Groningen field. The case of stress concentrations on the fault as a result of reservoir depletion in Groningen has been widely published, see for example Buijze et al. (2017), Poessé & van den Hoek (2020), van den Hoek and Poessé (2021), and van den Bogert (2015). Figure 3-1 shows the profile of the so-called “Shear Capacity Utilisation” (SCU) along the fault which is defined by

$$SCU = \frac{\text{Shear stress along the fault}}{\text{Maximum shear stress along the fault}} = \frac{\text{Shear stress along the fault}}{C + (\text{Normal stress on the fault}) \times \tan(\varphi)}$$

where C and φ are the cohesion and friction angle of the fault, respectively. The SCU can be viewed as a quantitative measure of how close the fault is to “failure” (activation), which is indicated by a value of SCU = 1. In Figure 3-1 it can be seen that there are shear stress concentrations, resulting in high SCU, at the top of the hanging wall reservoir (right) and the bottom of the foot wall reservoir (left). This is a well-known phenomenon that takes place along faults with nonzero offsets crossing depleting reservoirs, see again van den Bogert (2015), Poessé & van den Hoek (2020), (van den Hoek & Poessé, 2021), and TNO (2014). With progressing reservoir depletion beyond 75 bar, the SCU of the entire fault area between the top of the hanging wall (right) and bottom of the foot wall (left) becomes equal to one, which eventually could cause fault slip over this area. This potential movement along the fault does not directly imply that seismicity and small earthquakes will occur (Poessé & van den Hoek, 2020), (van den Hoek & Poessé, 2021).

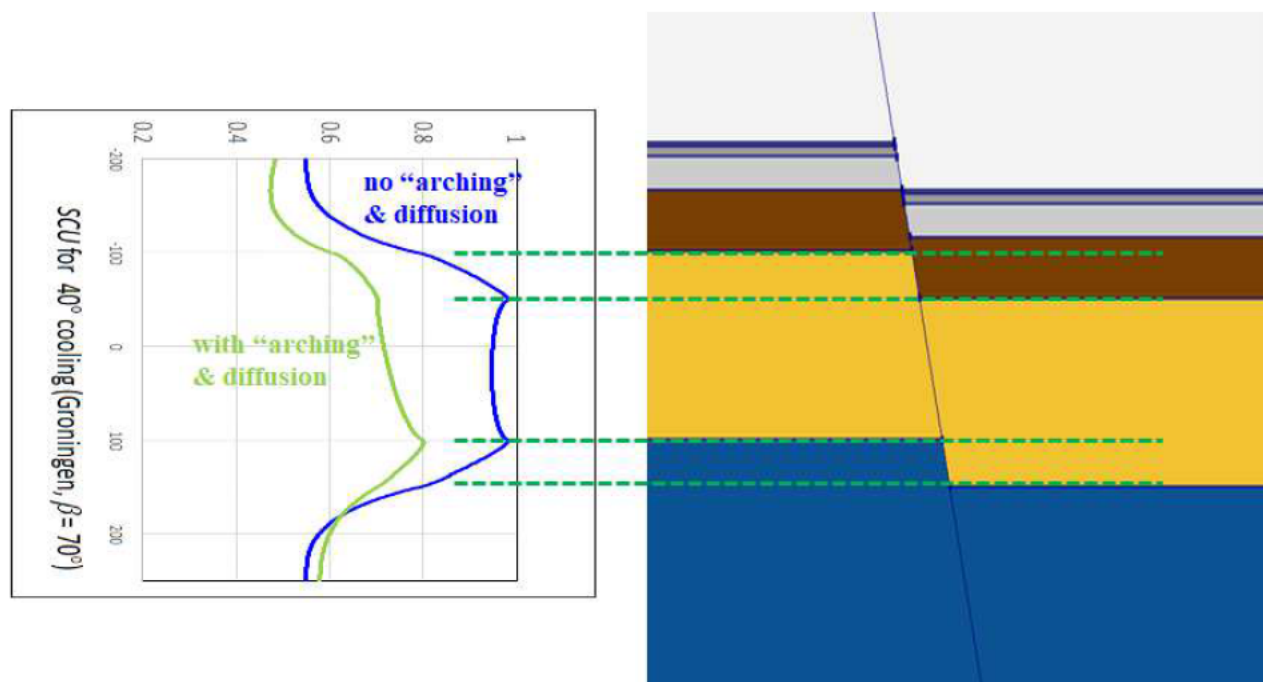


Figure 3-2 Profile of the computed “Shear Capacity Utilisation” (SCU) along the fault for a Groningen-field situation, with (hypothetical) 40°C reservoir cooling.

The effect of stress concentration along faults with nonzero offsets not only takes place as a result of reservoir depletion, but also as a result of reservoir cooling. Stress changes as an effect of reservoir cooling is illustrated Figure 3-2 for the same (Groningen) reservoir as Figure 3-1, but now for a (hypothetical) cooling by 40°C. However, an essential difference with (gas) reservoir depletion is that in this case, only a very limited part of the reservoir is cooled, even after around 30 years of operation. Moreover, as a result of thermal diffusion within the reservoir and from the cap- and base-rock, the temperature varies more

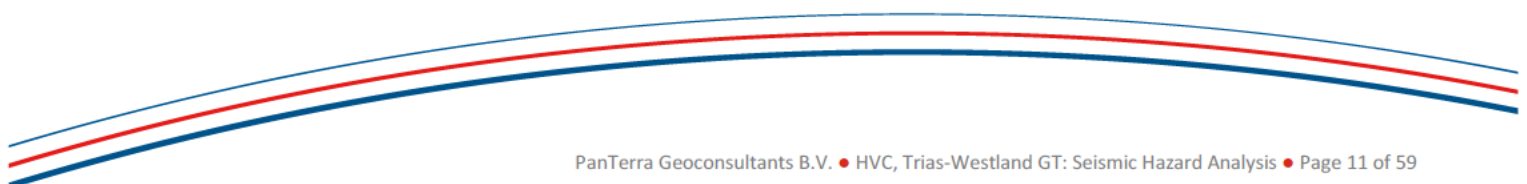
smoothly and large parts of the reservoir, especially further away from the injector, cool only partially. The finite size of the (partially) cooled reservoir results in arching by the non-cooled areas of the reservoir, and therefore the SCU at the fault can be significantly lower. This is illustrated in Figure 3-2. Here, the blue curve represents a situation where the entire reservoir has been cooled, whereas the green curve represents a situation where only a few hundred meters around the injector have been (partially) cooled. As will be shown below for the Trias-Westland cases, a cooled zone extent of a few hundred metres to a kilometer is realistic for a geothermal operation that lasts about 10-30 years.

3.2 (Probabilistic) Mohr-Coulomb modelling

The state of stress can be defined by the means the Mohr-circles and associated Mohr-Coulomb failure criterion. The Mohr-circle represents the state of stress for any given orientation in a 2D or 3D space, with as input the maximum, minimum and in case of 3D the intermediate stress. In the presence of a fault, a failure criterion can be defined by the cohesion and friction coefficient of this fault. If the state of stress in a specific orientation exceeds the failure criterion, shear slip movement may occur along the fault. The goal of the Mohr-Coulomb exercise is to know at what limit slip along the fault may occur which is a potential hazard coming from a subsurface operation.

Mohr-Coulomb only addresses the stress state at one point in space. In order to address parameter uncertainties, a probabilistic Mohr-Coulomb approach ("Mohr-Coulomb Monte-Carlo") is applied to the point along the fault where failure is most likely, i.e. the point with highest SCU. This can be considered a conservative approach because it only addresses the failure likelihood of *the "worst" point along the fault*, whereas fault slip requires failure ($SCU = 1$) over a larger contiguous fault area, just like in the Groningen depletion case.

The effect of local stress arching for a geothermal project is illustrated in Figure 3-2 and Figure 3-3. In the case of geothermal projects, the local higher stress concentrations along a fault can be offset by the fact that the stress perturbation is only on a local scale. This effect will diminish if the cooled zone becomes larger towards the extent that the whole reservoir becomes cooled.



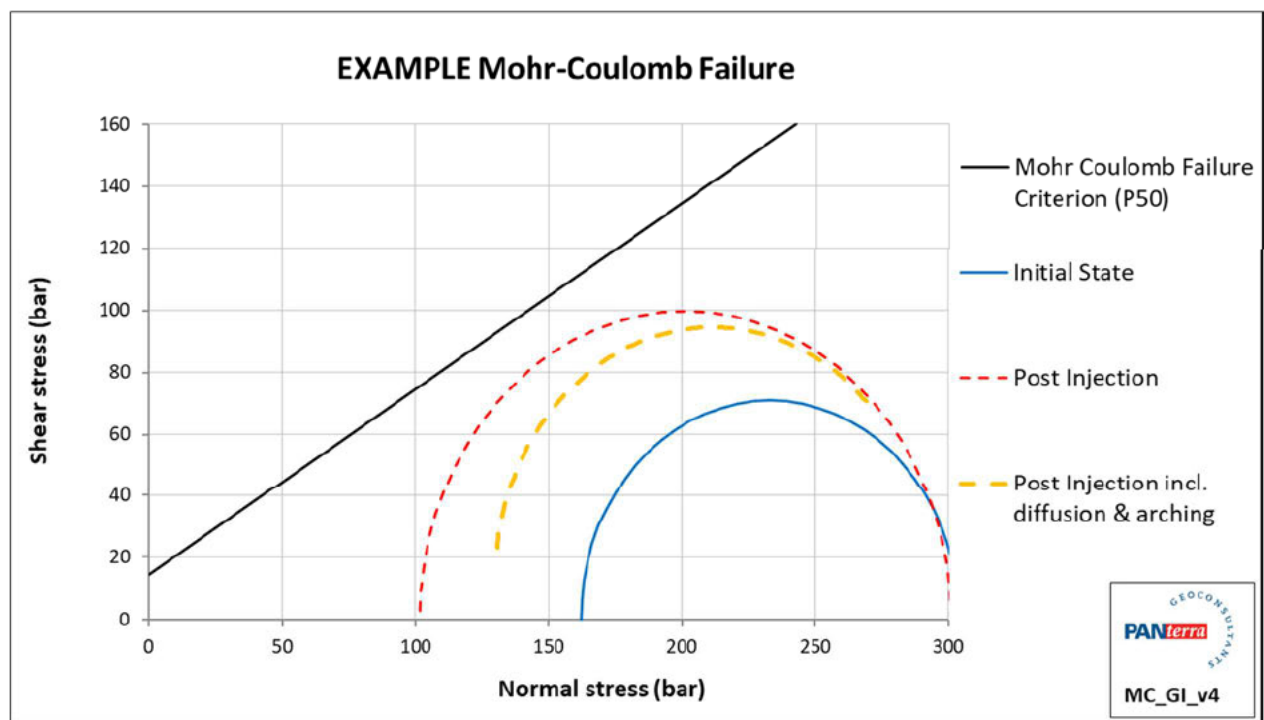
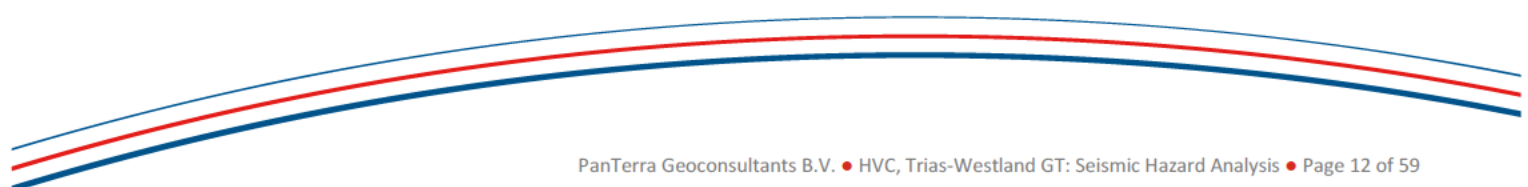


Figure 3-3 Mohr Coulomb model including temperature diffusion & arching. In the case of geothermal projects, the local higher stress concentrations along a fault can be offset by the fact that the stress perturbation is only on a local scale.

In a Mohr-Coulomb Monte-Carlo study, 1000 simulations are run on a large range of parameters covering the state of stress, production parameters, geological and rock parameters, fault parameters and arching and temperature diffusion. A triangular distribution is used to omit outliers as is consistent with the DoubletCalc approach, TNO (2014).

An example scenario is provided in Figure 3-4. The two Mohr-Circles are for reference and represent the median input (solid blue) and output (orange dashed) cases. The dots represent the output of the simulations where the red dots have an SCU above the P90-value and green dots have an SCU below the P10-value. Blue dots have SCU-values between P10 and P90-values. Any simulation exceeding the critical $SCU > 1$, and therefore exceeding the failure criterion, is indicated by a red square. The resulting P90, P50 and P10 failure criterion are displayed in the dashed linear lines. As the fault properties are varied for each individual simulation it may be possible that simulations exceed the P90 or even the P50 failure criterion without reaching the critical $SCU > 1$ as this is calculated separately for each individual scenario.



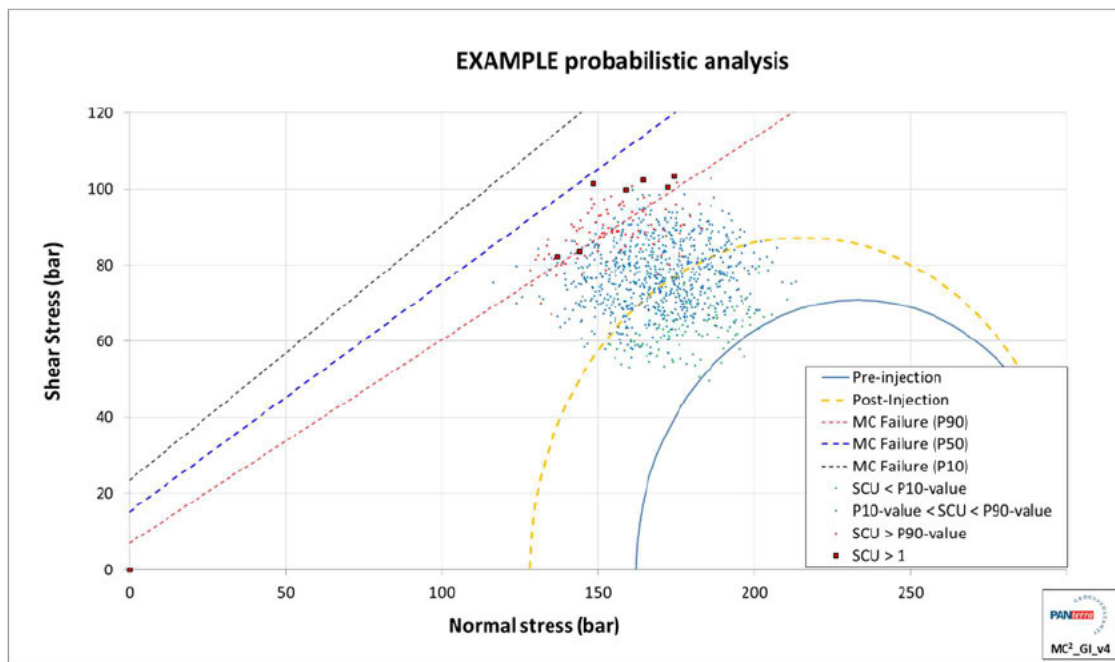


Figure 3-4 Mohr Coulomb Monte Carlo (MC^2) model. The two Mohr-Circles are for reference and represent the median input (solid blue) and output (orange dashed) cases.

3.3 Temperature profile

The temperature profile is computed by our in-house fine-grid radial numerical reservoir simulation. An example is shown in Fig. 3-5, which shows that our model predicts a more conservative (= larger) cold front radius than DoubletCalc2D. For reference, also the radius based on an analytical heat balance calculation is included. In the absence of thermal diffusion from cap- and baserock, the numerically computed centre of the cold front should coincide with this line.

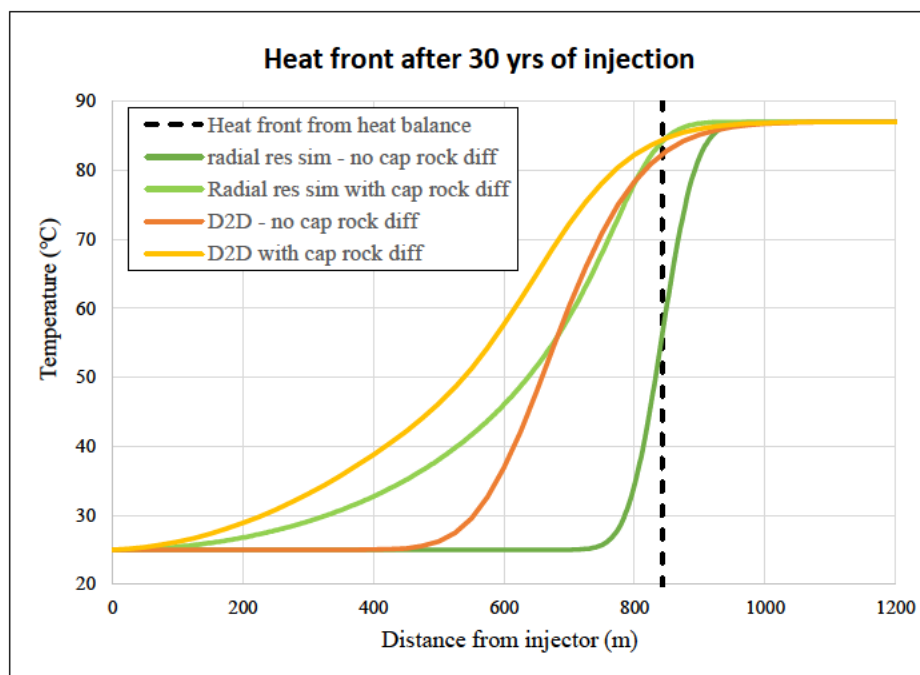


Figure 3-5 Temperature profiles as computed by our model and by DoubletCalc2D for NLW-GT-01 with injection rate 430 m³/hr with 80% uptime, both without and with thermal diffusion from cap- and baserock. Dashed line represents the position of the heat front based on analytical heat balance calculation. In the absence of thermal diffusion from cap- and baserock, the centre of the cold front should coincide with this line.

4 Geological and geomechanical setting

4.1 Geological setting

The Trias-Westland doublets were drilled in 2017-2018 (NLW-GT-01 & NLW-GT-02) and 2020 (NLW-GT-03 & NLW-GT-04). The doublets are situated in the West Netherlands Basin (WNB, Figure 4-1), which is an inverted rift basin (de Jager et al., 1996). Sediments in this basin range in age from Jurassic to recent and are overlying Triassic and older sediments. The reservoir target is the Early Cretaceous Nieuwerkerk formation, more specifically the Delft Sandstone and upper Alblasserdam Members. The Delft Sandstone and the sandstones in the Alblasserdam have good reservoir properties in general.

In the Late Cretaceous, during the deposition of the Chalk Group, the West Netherlands Basin was inverted. This was accompanied by compressional movements and resulted in convergent oblique-slip faulting, general uplift, erosion and basin inversion, which reactivated pre-existing normal faults. The major tectonic feature in the region of the license is a NW-SE trending graben. The structure is bounded by two faults with >100m offset (i.e., Fault 1 and Fault 2 as indicated in Figure 4-2).

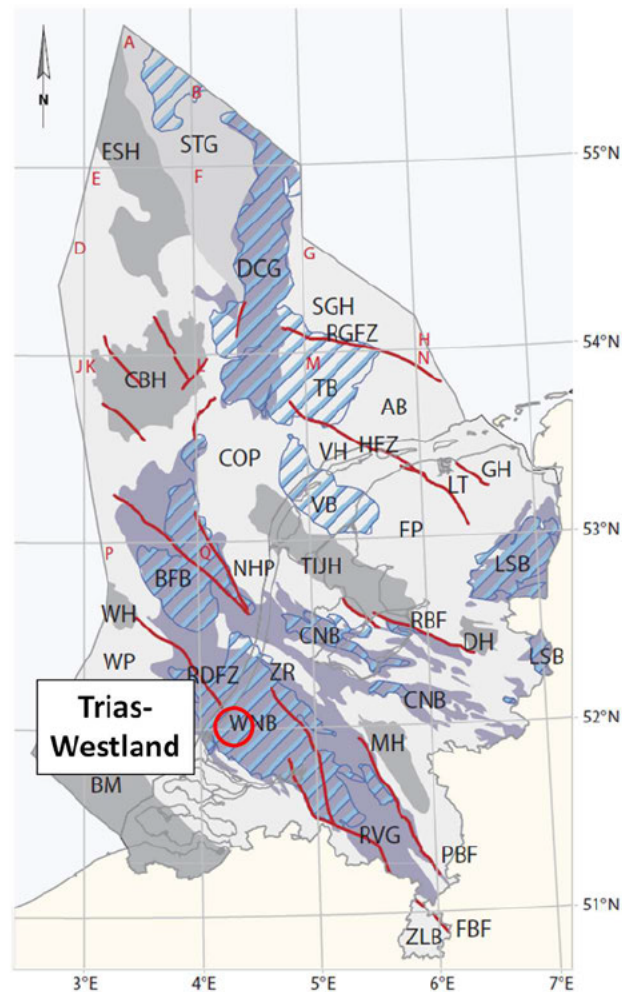
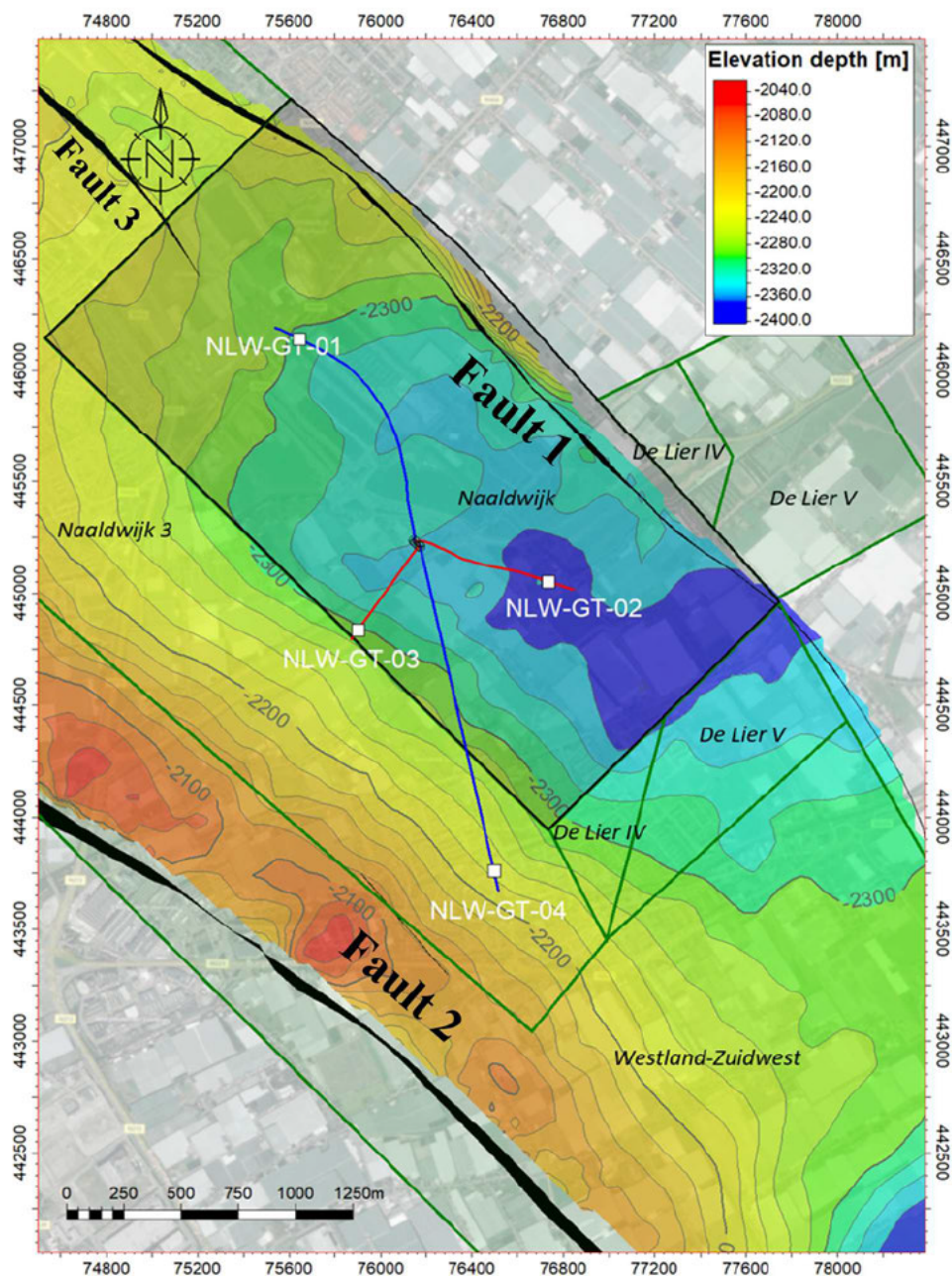


Figure 4-1 Structural elements and major fault zones as present during the Late Jurassic-Early Cretaceous (Duin et al., 2006).

At reservoir level, injector NLW-GT-01 is located approximately 750 m away from Fault 1 and around 800m from the much smaller Fault 3 (Figure 4-2 and Table 4-1). There is some uncertainty on the presence and exact extent of Fault 3, but it was taken into account in this study nonetheless. Injector NLW-GT-04 is located approximately 600m away from Fault 2. Figure 4-2 and Figure 4-3 show seismic cross sections through the injection wells at reservoir level, perpendicular to the azimuth of the faults. No faults are observed between the four wells. The two major faults bounding the structure are regarded as sealing because of their large throw. Possible subseismic faults are unlikely to be sealing since the reservoir thickness is greater than the seismic resolution.



Figuur 4-2 Top Delft reservoir depth map of the target area with planned wells, penetration points (white squares) and faultlines (black, Faults 1–3).

Table 4-1 Faults and geometrical information for Trias-Westland injectors

Fault	Injector	Offset (m)	Distance to injector @ top reservoir (m)
1	NLW-GT-01	~ 120	~ 750
2	NLW-GT-04	~ 100	~ 600
3	NLW-GT-01	~ 30	~ 800

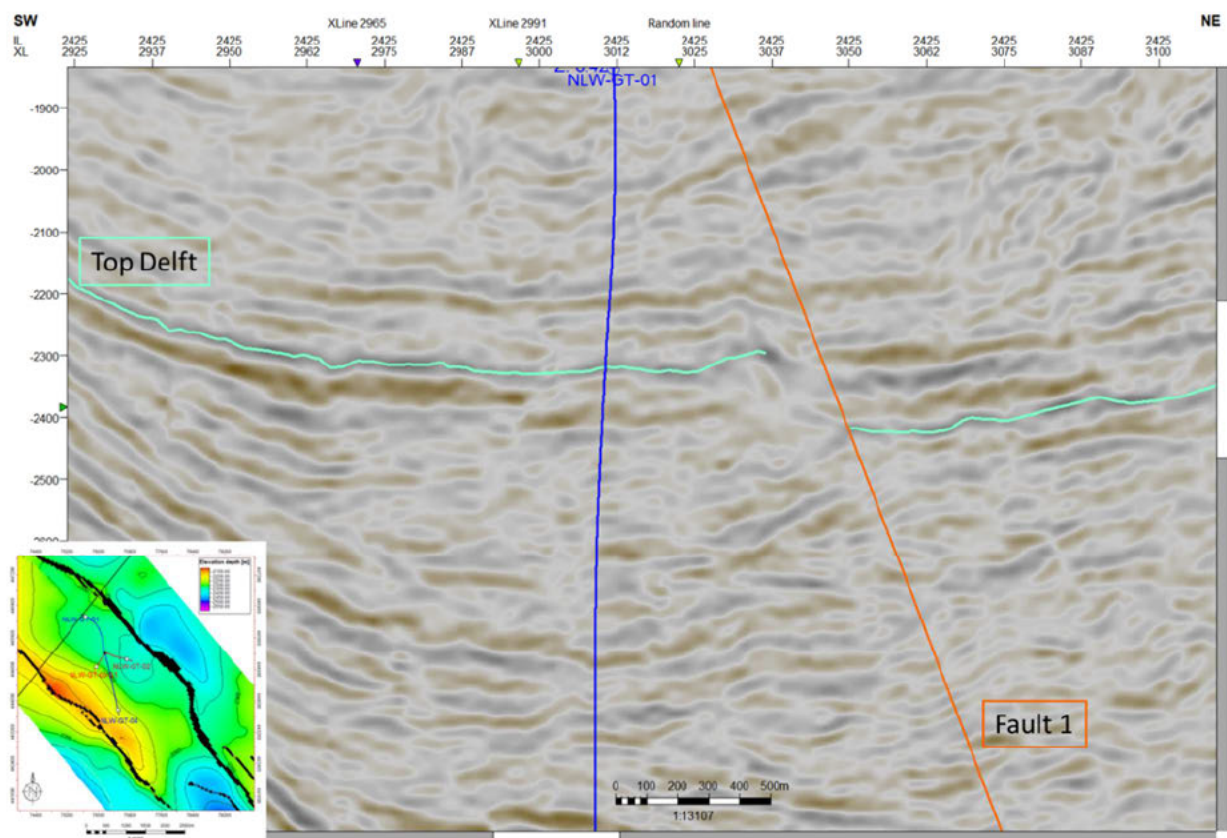


Figure 4-2 Seismic cross-section (L3NAM2016CR, IL 2425) perpendicular to Fault 1 with projection of well NLW-GT-01. Location of the seismic line indicated on inset map.

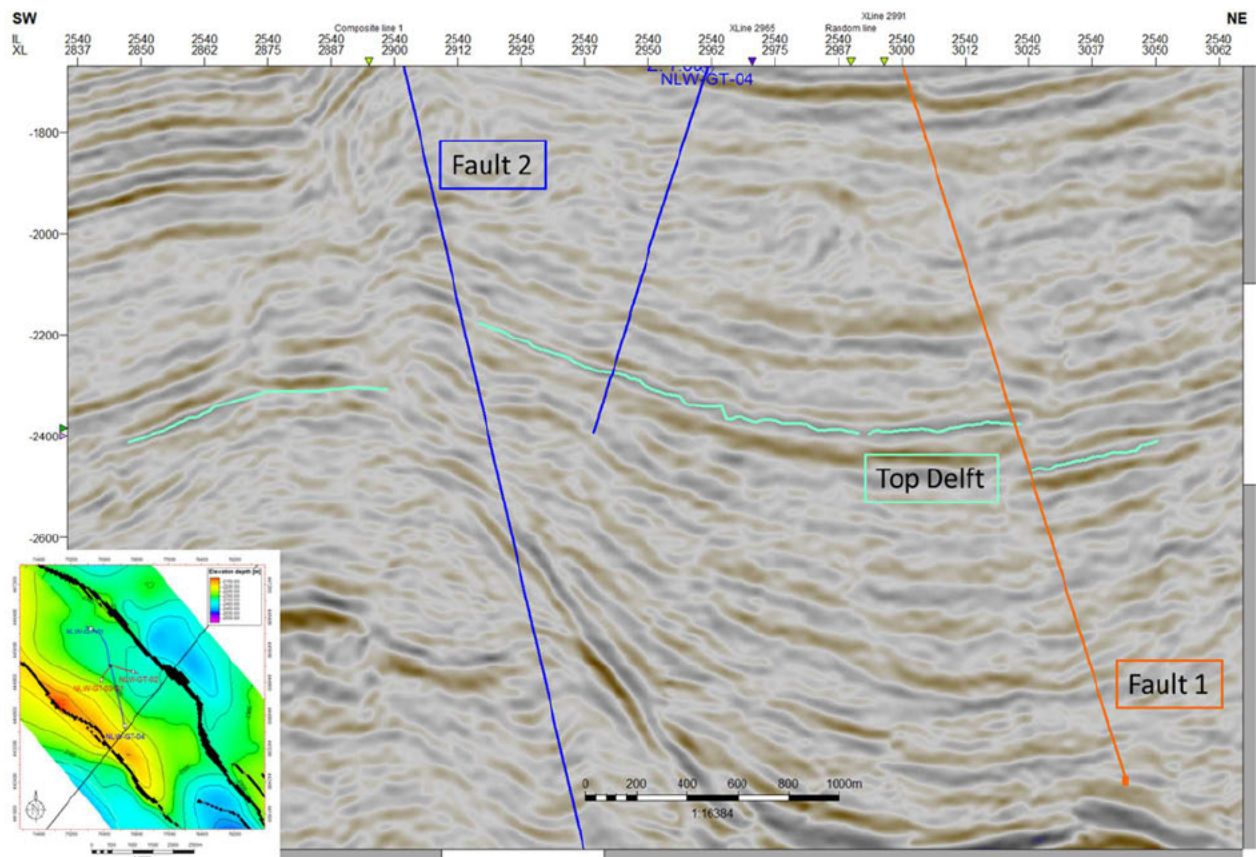


Figure 4-3 Seismic cross-section (L3NAM2016CR, IL 2540) perpendicular to Fault 4 with projection of well NLW-GT-04. Location of the seismic line indicated on inset map.

4.2 In-situ stress estimates

In-situ stress trends are mostly based on measured leak-off pressures as reported by Verweij et al. (2012). These authors distinguished a number of different geological areas within the Netherlands. For each of these areas, an in-situ stress trend map was generated. The geological area that is relevant for the current discussion is the so-called West Netherlands Basin for which the data are given in Figure 4-4. This figure displays measured Formation Integrity Tests (FIT) / leak-off pressure tests (LOT) as a function of depth in the West Netherlands platform area.

Until a depth of around 1500 m, the trend closely follows the well-known minimum in-situ stress gradient of 0.158 bar/m (0.7 psi/ft) for an extensional stress regime, whilst at greater depths it starts to bend somewhat towards higher stresses.

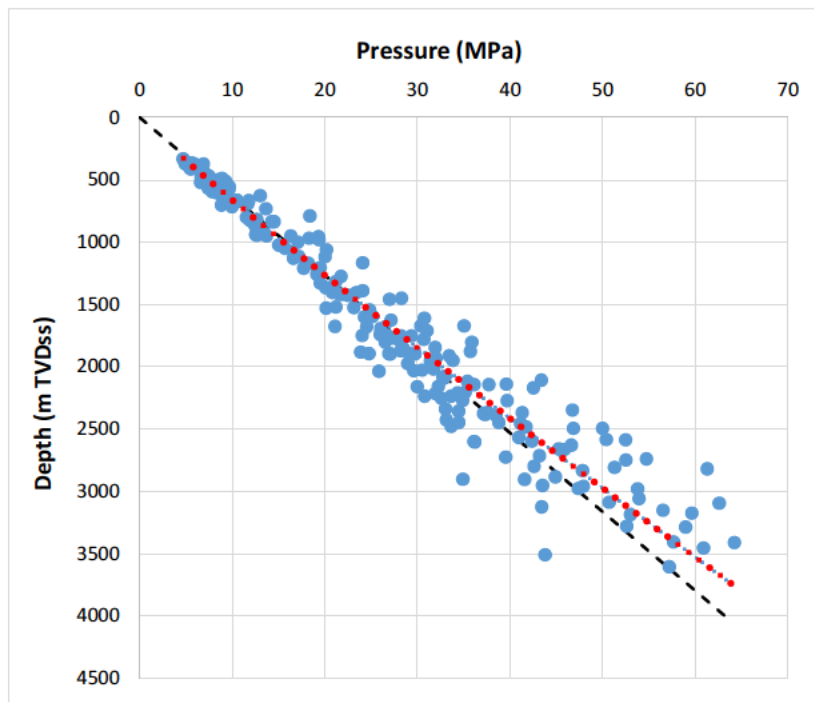


Figure 4-4 Minimum in-situ stress versus depth trend in the West Netherlands Basin area based on Formation Integrity Tests (FIT) / Leak-Off Tests (Verweij et al., 2012). Red-dashed line: trend line based on leak-off tests. Black-dashed line: trend line of 0.158 bar/m.

From the dataset shown in Figure 4-4, a subset was chosen from wells in the neighborhood of Trias-Westland. The wells chosen plus the resulting stress trend are displayed in Figure 4-5. As can be seen, the baseline trend falls more or less on top of the well-known trend of 0.158 bar/m for an extensional stress regime, with a standard deviation of 0.02 bar/m.

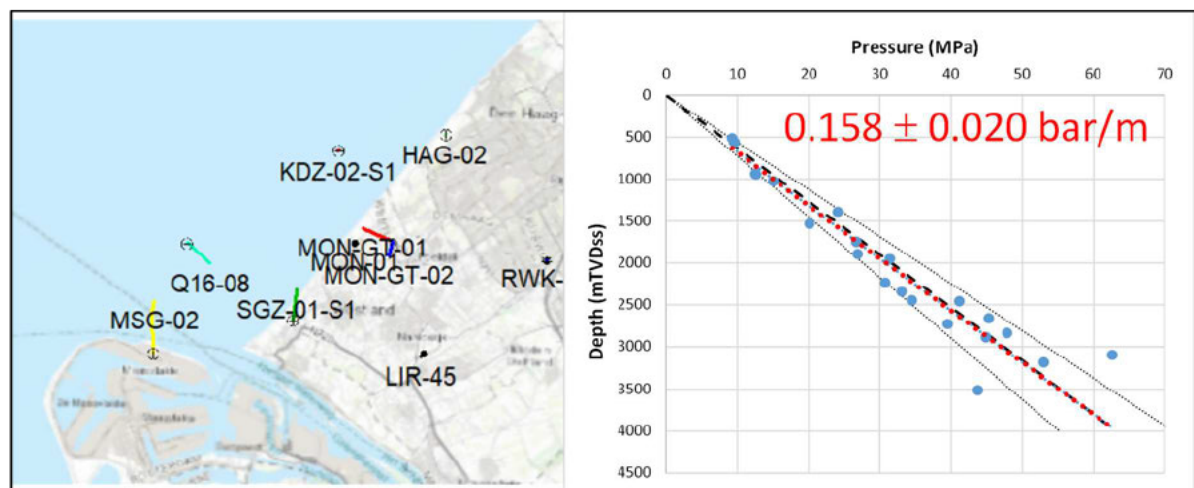


Figure 4-5 Minimum in-situ stress versus depth trend in the West Netherlands Basin area based on Formation Integrity Tests (FIT) / Leak-Off Tests from wells in the neighborhood of Trias-Westland.

4.3 Reservoir Parameters

Reservoir parameters have influence on both the production prognosis as the geomechanical calculation and will be shortly discussed below.

4.3.1 Porosity and permeability

Porosity based on petrophysics of is expected to be 19 % in the Delft. The permeability used is 700 mD for the Delft around NLW-GT-01 and 800 mD around NLW-GT-04.

4.3.2 Depth

Top of the reservoir is reported at 2313 m TVD for the Delft around NLW-GT-01 and 2232 m TVD around NLW-GT-04.

4.3.3 Thickness

The median thickness of the Delft is estimated to be 78 m around NLW-GT-01 and 60 m around NLW-GT-04.

4.3.4 Temperature

Based on data from Doubletcalc, reservoirs temperature has been set to 87°C around NLW-GT-01 and 85°C around NLW-GT-04.

4.3.5 Thermo-elastic constant

In response to temperature changes, the reservoir rock will tend to expand (heating) or shrink (cooling). Because in the subsurface there is no 'room' in the horizontal direction to expand or shrink ('plane strain'), this results in a change of total horizontal stress that is given by

$$\Delta\sigma_h = A_T \cdot \Delta T \quad (1)$$

where ΔT is the temperature change (negative for cooling) and A_T is the "thermo-elastic constant" (in bar/°C). Equation (1) is only valid if the entire reservoir has been cooled. When only part of the reservoir has been cooled, a geometry correction factor is applied. This geometry correction factor is also included in the fracture simulator.

The thermo-elastic constant is a material property of the rock. Under the assumption of perfectly elastic behaviour of the rock, both at matrix level and at grain level, this constant can be expressed as

$$A_T = \frac{\alpha E}{1-\nu} \quad (2)$$

where

- α is the linear thermal expansion coefficient (in °C⁻¹)
- E is Young's modulus (in bar)
- ν is poisson's ratio (dimensionless)

suggesting that A_T is linearly proportional to Young's modulus E if the thermal expansion coefficient α is assumed equal for all types of rocks under all circumstances (stress, temperature, ..).

Not many measurements of this constant have been carried out. Koning (1988) and Perkins & Gonzalez (1985) used values for A_T in the range 0.9-1.0 bar/°C for 'medium-strength' reservoir sandstones with

Young's moduli in the range 10-15 GPa. For deep, tight rocks (> 10000 ft TVD), values of A_T in the range 1.5-2.0 bar/°C have been used in a number of oil field studies with waterflooding, both in Prudhoe Bay, Alaska (Stevens et al., 2000) and in the North Sea (Santarelli et al., 2008; Svendsen et al., 1991). On the other hand, in the Eider oil field, North Sea (~ 9000 ft TVss) a value of $A_T = 0.6$ bar/°C was derived based on step-rate tests, whilst in a carbonate / mudstone reservoir in the Middle East (~6500 ft tVD), a range of 0.4-0.9 bar/°C was measured on different core plugs. From the above we derive an average value for A_T of $\sim 1.0 \pm 0.5$ bar/°C, which may increase up to ~ 2.0 bar/°C for (very) tight rocks. In the current study a value of 1.0 ± 0.5 bar/°C is used

4.3.6 Poro-elastic constant

In response to pressure changes, the reservoir rock will tend to expand (pressurisation) or shrink (depletion). Because in the subsurface there is no 'room' in the horizontal direction to expand or shrink ('plane strain'), this results in a change of total horizontal stress that is given by

$$\Delta\sigma_h = A_p \cdot \Delta p \quad (3)$$

where Δp is the pressure change (negative for depletion) and A_p is the "poro-elastic constant" (dimensionless). Equation (3) is only valid if the entire reservoir has been pressurised or depleted. When only part of the reservoir has been pressurised / depleted, a geometry correction factor is applied. This geometry correction factor is also included in the fracture simulator.

The poro-elastic constant is a material property of the rock. Under the assumption of perfectly elastic behaviour of the rock, both at matrix level and at grain level, this constant can be expressed as

$$A_p = (1 - \beta) \frac{1-2\nu}{1-\nu} \quad (4)$$

where

- $\beta = \frac{K_m}{K_s}$
- K_m is the bulk modulus of the rock matrix (bar)
- K_s is the bulk modulus of the solid rock grains (bar)

In practice, the above equation is only of qualitative value. Laboratory tests have shown that A_p often deviates significantly from the formula (4). Typical values are in the range 0.5-0.8. In the current study a value of 0.6 is used. Contrary to the thermo-elastic constant A_T , the value used for A_p is less critical because in a typical geothermal doublet, only a very small area around the injector is pressurised and only a small area around the producer is "depleted". On the other hand, a significant area around the injector will be cooled during the field life, thus making the parameter A_T a more critical one.

4.3.7 Fault parameters

Fault stability is defined by the cohesion and friction coefficient of the fault.

4.3.7.1 Cohesion

As a conservative low base, zero cohesion is assumed. For the probabilistic analysis a range of 0-15-30 bar is considered. A cohesion of 15 bar can be considered as 'typical' for weakly consolidated rock.

4.3.7.2 Friction coefficient

No measurements on fault properties are available. A typical sandstone has a friction coefficient in the order of ~0.6 (Hunfeld et al., 2017). Uncertainty ranges on sandstone are reported between 0.48 and 0.72 (Samuelson & Spiers, 2012). A range of 0.48-0.60-0.72 is used. No hardening and/or softening of the fault is considered in this analysis.

5 Results

5.1 Injector well NLW-GT-01 – injection into the Delft formation – Fault 1

Results of Fault 1 stability will be presented for two different injection rates: 430 m³/hr @ 80% uptime (effectively 344 m³/hr) and 300 m³/hr @ 80% uptime (effectively 240 m³/hr). For both injection rates, results will be presented for a permeable Fault 1 and an impermeable Fault 1.

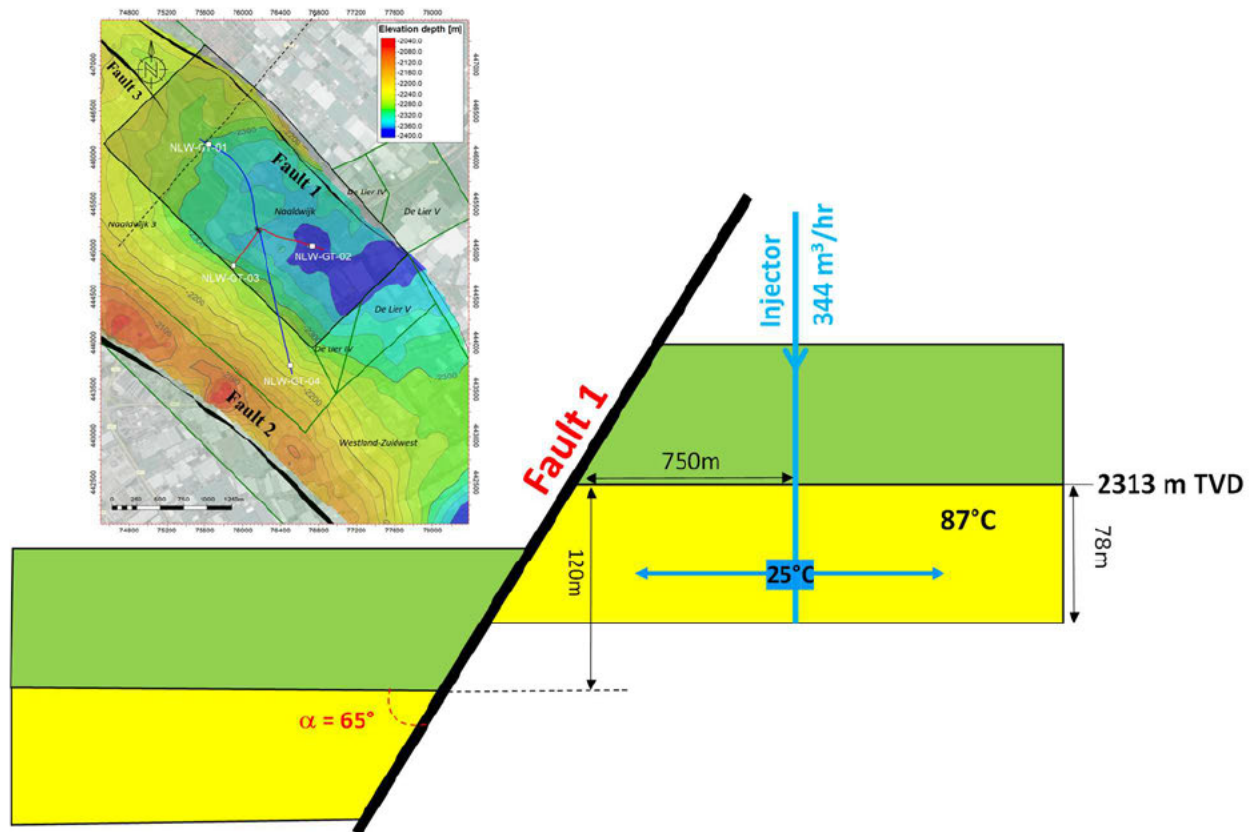


Figure 5-1 NLW-GT-01 Delft Fault 1: top view and side view (cross section) of injector and fault 1 along the dashed line indicated in the top view.

5.1.1 Injection rate 344 m³/hr and permeable Fault 1

5.1.1.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Figure 5-2. The cooled zone is not an abrupt front but rather influenced by thermal diffusion, both within the reservoir and from the cap- and baserock into the reservoir.

After 30 years of injection we observe a temperature alteration up to ~900 m. This is considered the cold water “front”. Fault 1 is expected at 750 m. This scenario is schematically depicted in Figure 5-1.

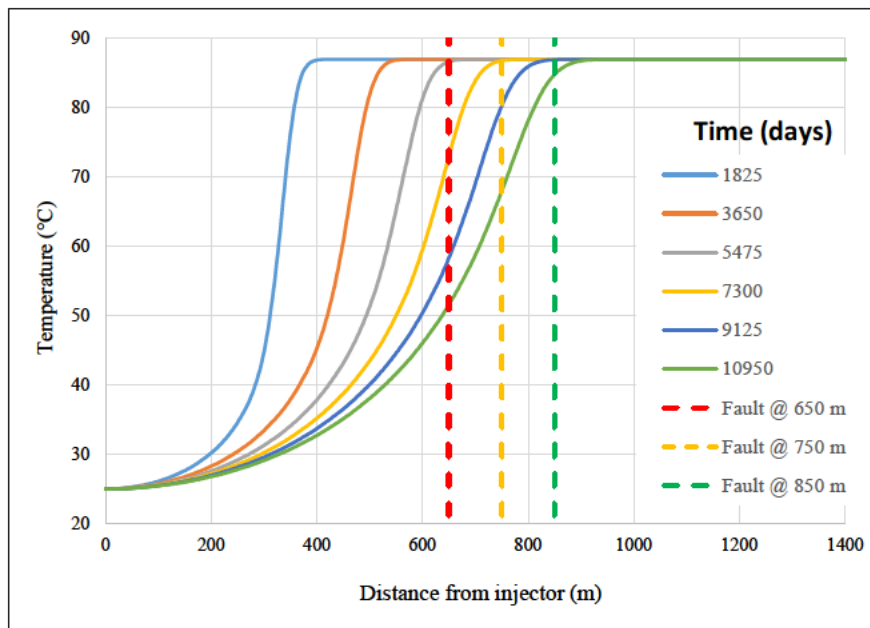


Figure 5-2 Temperature profile in the reservoir away from the injector after 30 years of injection of 344 m³/hr for a permeable Fault 1.

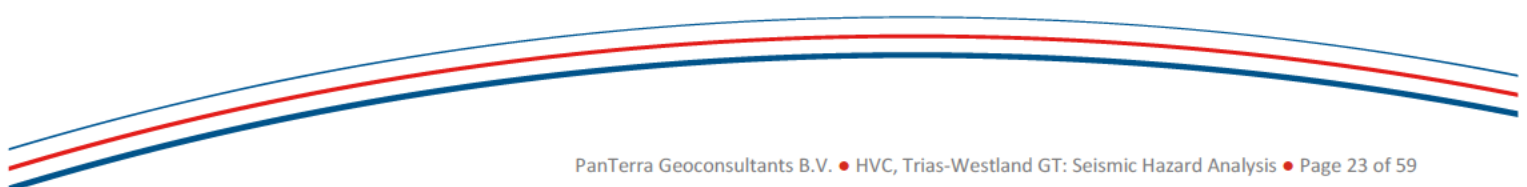
5.1.1.2 Deterministic analysis

The methodology as described in Section 3.1 is applied to estimate the impact of the cooling on the Shear Capacity Utilisation (SCU). In order to take into account the effect of partial cooling, the entire temperature profile in the cooled zones to the left and to the right of the fault is computed. Subsequently, the thermo-elastic stress change on the fault resulting from this temperature profile is calculated. As a fault position is a matter of interpretation and faults often display ‘damage zones’ an uncertainty was taken into account in the fault position of ± 100 m.

The results are given in Figure 5-3, where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 344 m³/hr. As can be seen, the maximum SCU for the base case (at vertical coordinate $x \approx 30$ m) is around 0.75 which is still significantly below 1. Varying the fault distance over ± 100 m with respect to base case of 750 m from injector results in an SCU-variation between 0.64 and 0.91.

Fig. 5-4 shows a deterministic failure analysis for the “worst” point on the SCU curve of Fig. 5-3. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 344 m³/hr for a permeable fault at 750 m. The red dashed Mohr circle is obtained by assuming a uniform cooling down to the injection temperature of 25°C across the entire reservoir. The yellow dashed Mohr circle includes the actual change of state of stress as a result of the cooled area, i.e. it includes the impact of stress arching by uncooled areas further away from the injector. Also, the approach presented here includes the impact of stress concentrations along the fault.

It should be noted that the impact of stress arching is fairly pronounced in this case (Fig. 5-4). This can be explained by the fact that the lateral extent of the cooled zone around the fault is not (yet) very large compared to the reservoir thickness. As will be shown below, for lower injection rates, the cooled area within the reservoir will be smaller, resulting in a higher degree of arching, in line with expectations.



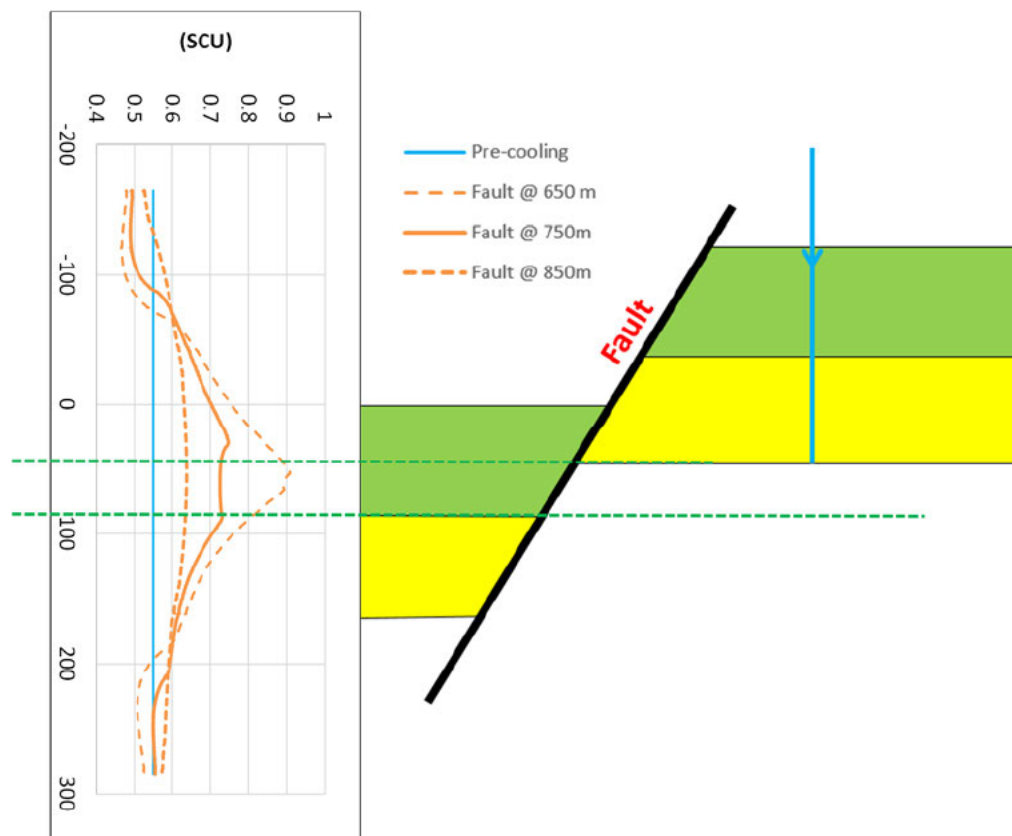


Figure 5-3 Computed SCU along the fault for injection rate 344 m³/hr and permeable Fault 1. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ±100m.

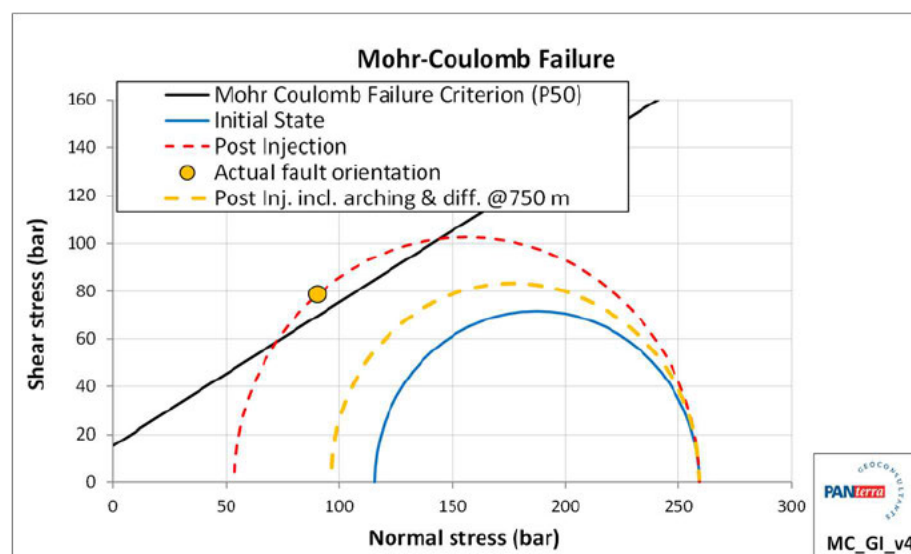


Figure 5-4 Mohr circles for injection rate 344 m³/hr and permeable Fault 1 at the “worst” point along the fault (see fig. 5-3).

5.1.1.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are shown in Table 5-1, which displays the input parameters for the probabilistic analysis of the Delft formation and Fault 1, including their low-med-high values. The parameters and reasoning have been discussed in section 4.3.

Table 5-1 Input parameters for probabilistic analysis of the Delft formation and Fault 1. See text for discussion.

	Parameter	Min	Median	Max
Rock Parameters	Reservoir Temperature (°C)	84	87	90
	Thermoelastic coefficient (bar/°C)	0.5	1.0	1.5
	Vertical stress gradient (bar/m)	0.21	0.22	0.23
	Horizontal stress gradient (bar/m)	0.144	0.158	0.189
Fault Parameters	Cohesion (bar)	0	15	30
	Friction coefficient (-)	0.48	0.60	0.72
	Dip (degrees)	55	65	75
	Distance from injector (m)	650	750	850

The results of this analysis are shown in Figure 5-5 and Figure 5-6. The majority of SCU values seen are in the 0.4-0.9 range, with 7% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 20% an SCU > 1 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 344 m³/hr, the probability of activation of Fault 1 by injecting 25°C water into the Delft formation via NLW-GT-01 can be considered non-negligible.

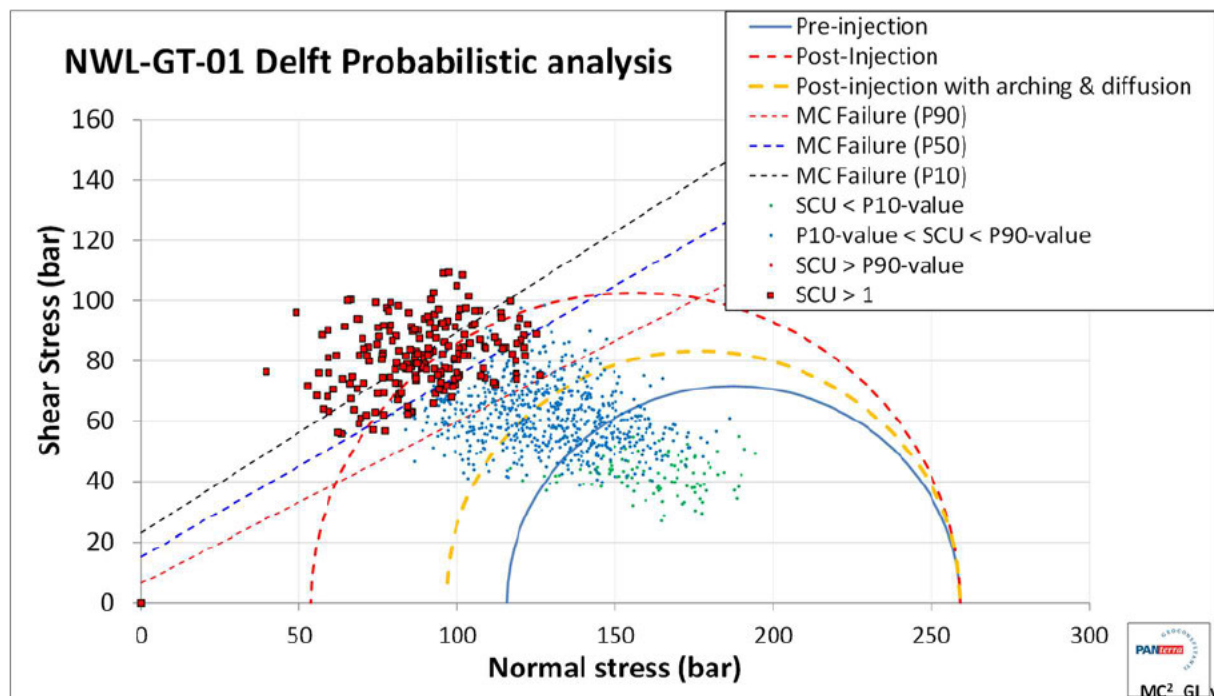


Figure 5-5 Results of Mohr-Coulomb Monte-Carlo for cooling around a permeable Fault 1 as a result of injection into well NLW-GT-01, after 30 years of injection at 344 m³/hr. The dots represent the simulations, colours indicating the P10, P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

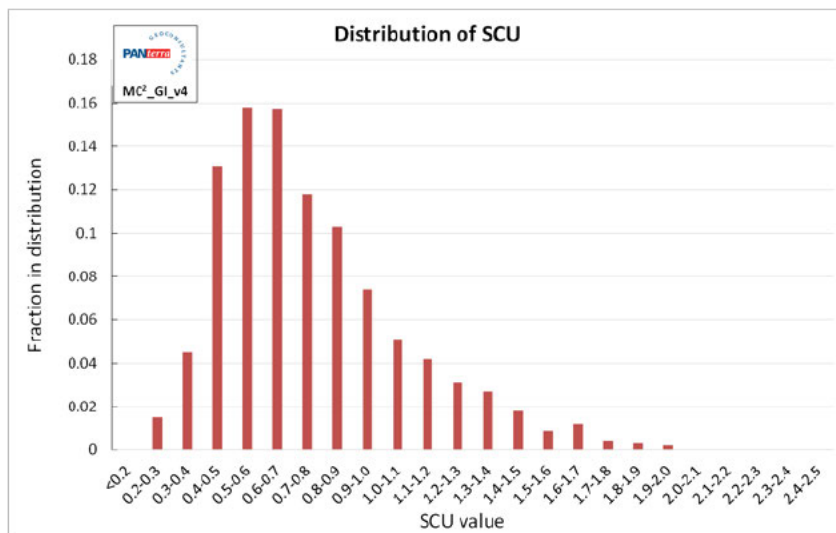


Figure 5-6. Probability diagram of the simulated SCU values after 30 years of injection at 344 m³/hr. Pemeable Fault 1. The bulk of the values are in between 0.4 and 0.9, with 7% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 20% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

5.1.2 Injection rate 344 m³/hr and impermeable Fault 1

5.1.2.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Figure 5-7 for the case of an impermeable fault at 750 m from the injector. In this case, the flood front (and therefore cold front) does not penetrate beyond the fault.

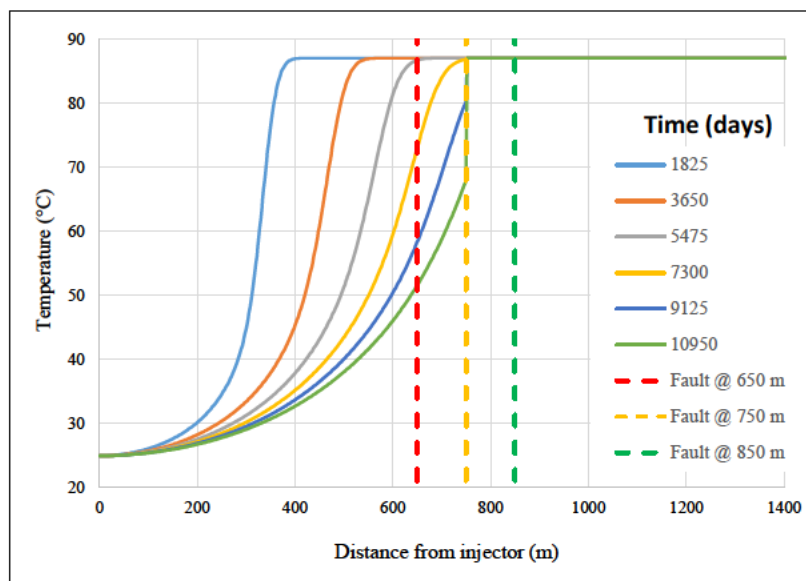


Figure 5-7 Temperature profile in the reservoir away from the injector after 30 years of injection of 344 m³/hr for the case of an impermeable Fault 1 at 750 m from the injector.

5.1.2.2 Deterministic analysis

Results are given in Figure 5-8 where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 344 m³/hr. As can be seen, the maximum SCU for the base case (at vertical coordinate x ≈ 80-90 m) is

around 0.72 which is still significantly below 1. Varying the fault distance over ± 100 m with respect to base case of 750 m from injector results in an SCU-variation between 0.64 and 0.79.

Figure 5-9 shows a deterministic failure analysis for the “worst” point on the SCU curve of Figure 5-8. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at $344 \text{ m}^3/\text{hr}$ for an impermeable fault at 750 m. The impact of stress arching is slightly more pronounced in this case (Figure 5-9) than in the case of a permeable fault (Fig. 5-4), as can be seen from the (slightly) smaller dashed yellow Mohr-Coulomb circle. This can be explained by the fact that in this case the cooled zone has not extended beyond the fault.

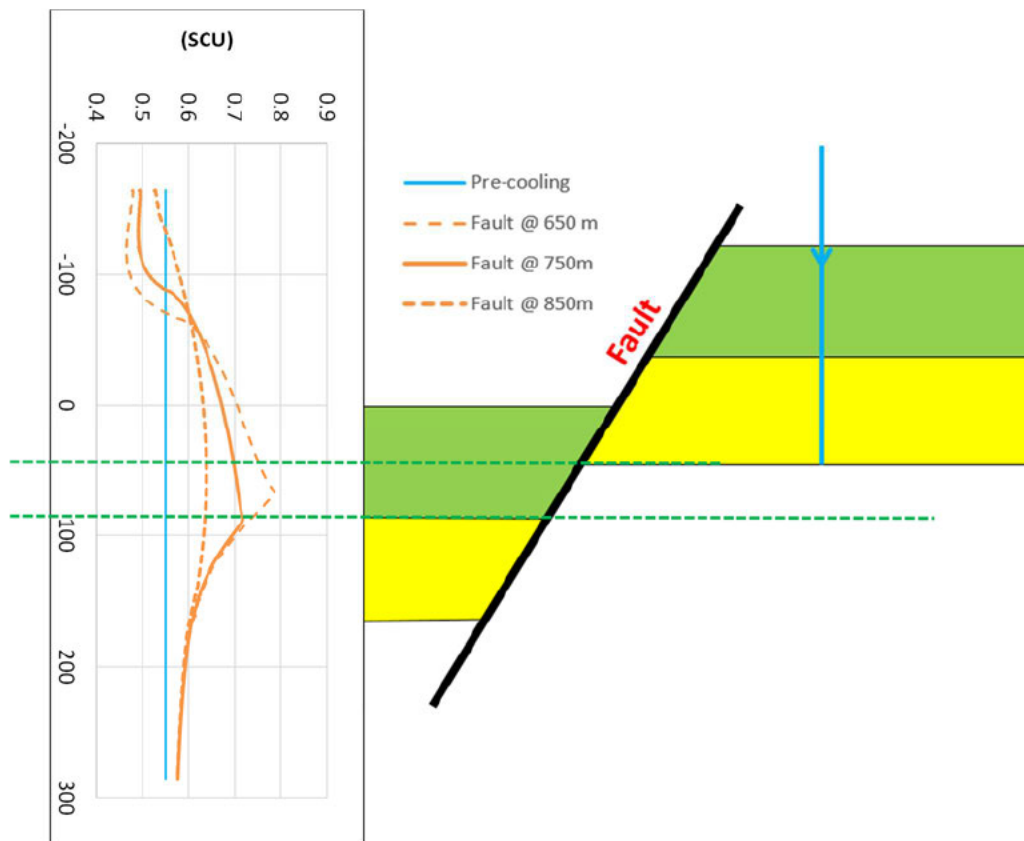


Figure 5-8 Computed SCU along the fault for injection rate $344 \text{ m}^3/\text{hr}$ and impermeable Fault 1. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of $\pm 100\text{m}$.

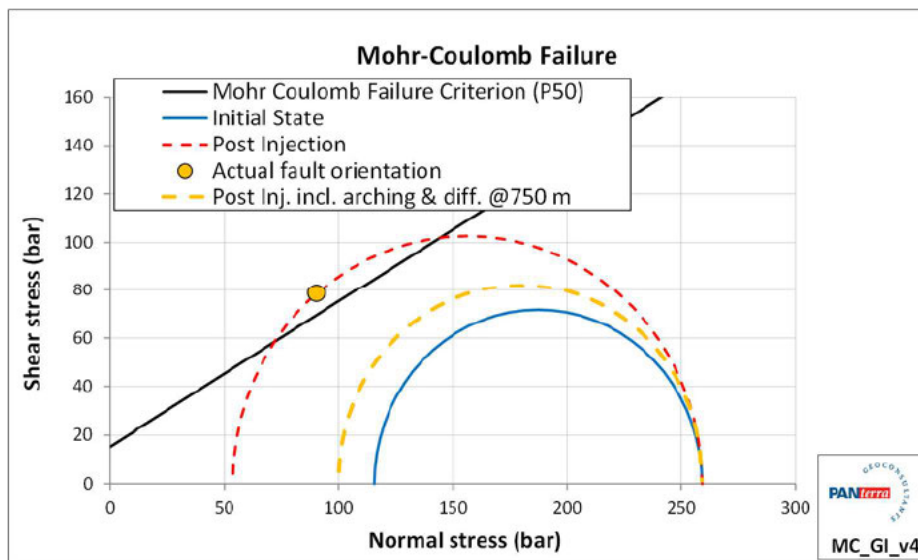


Fig. 5-9 Mohr circles for injection rate 344 m³/hr and impermeable Fault 1 at the “worst” point along the fault (see fig. 5-8).

5.1.2.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are the same as for the case of a permeable fault and shown in Table 5-1 above.

The results of this analysis are shown in Fig. 5-9 and Fig. 5-10. The majority of SCU values seen are in the 0.4-0.9 range, with 7% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 14% an SCU > 1 (based on the P90 Mohr-Coulomb failure line).

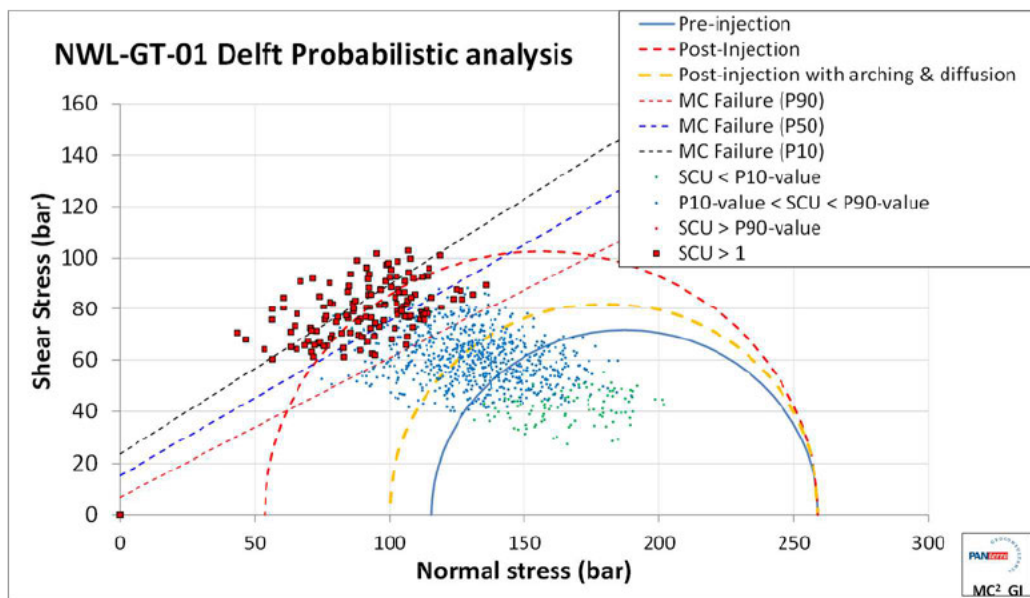


Figure 5-10 Results of Mohr-Coulomb Monte-Carlo for cooling around impermeable Fault 1 as a result of injection into well NLW-GT-01, after 30 years of injection at 344 m³/hr. The dots represent the simulations, colours indicating the P10,P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

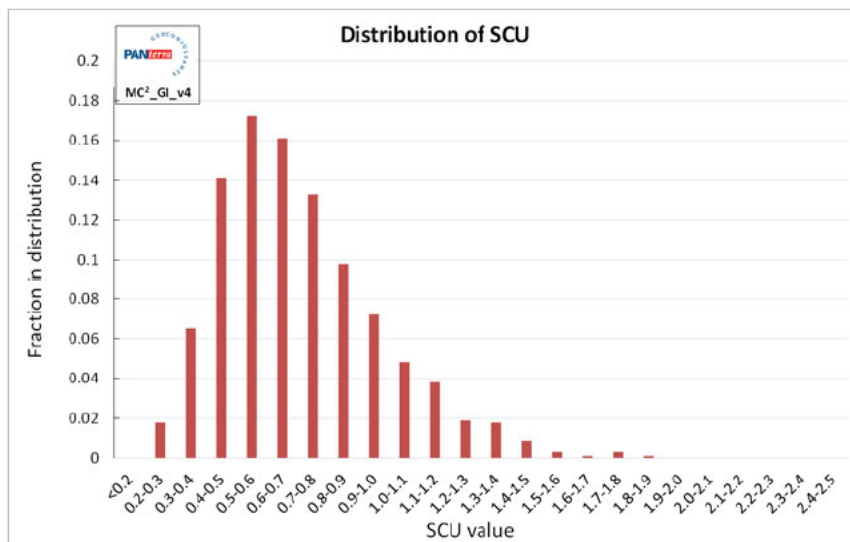


Figure 5-11. Probability diagram of the simulated SCU values after 30 years of injection at 344 m³/hr. Impermeable Fault 1. The bulk of the values are in between 0.4 and 0.9, with 7% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 14% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 344 m³/hr, the probability of activation of Fault 1 by injecting 25°C water into the Delft formation via NLW-GT-01 can be considered non-negligible. The probability of fault activation for an impermeable Fault 1 (14%) is slightly below that for a permeable Fault 1 (20%). This small difference can be explained by the fact that for a permeable Fault 1, the cold front after 30 years of injection has not penetrated very far into the part of the reservoir beyond the fault (refer to Figure 5-2).

5.1.3 Injection rate 240 m³/hr and permeable Fault 1

5.1.3.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Figure 5-12. for the case of a permeable fault at 750 m from the injector. After 30 years of injection we observe a temperature alteration up to ~750 m.

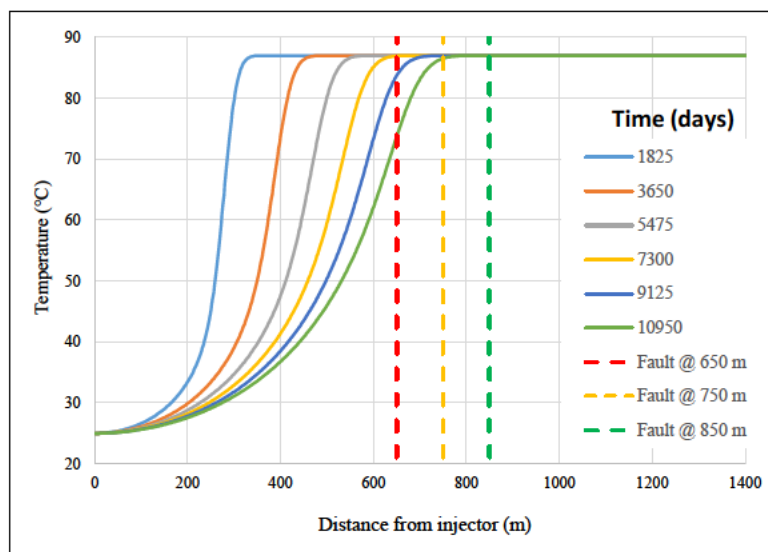


Figure 5-12 Temperature profile in the reservoir away from the injector after 30 years of 240 m³/hr injection for the case of a permeable Fault 1 at 750 m from the injector.

5.1.3.2 Deterministic analysis

Results are given in Fig. 5-13 where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 240 m³/hr. As can be seen, the maximum SCU for the base case (at vertical coordinate $x \approx 50$ m) is around 0.62 which is still significantly below 1. Varying the fault distance over ± 100 m with respect to base case of 750 m from injector results in an SCU-variation between 0.59 and 0.71.

Fig. 5-14 shows a deterministic failure analysis for the “worst” point on the SCU curve of Fig. 5-13. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 240 m³/hr for an impermeable fault at 750 m. The impact of stress arching is more pronounced in this case (Figure 5-14) than in the case of 344 m³/hr and impermeable fault (Fig. 5-9), as can be seen from the smaller dashed yellow Mohr-Coulomb circle. This can be explained by the fact that in this case the fault is only “touched” by the tip of the cooled zone, where temperatures are still close to reservoir temperature.

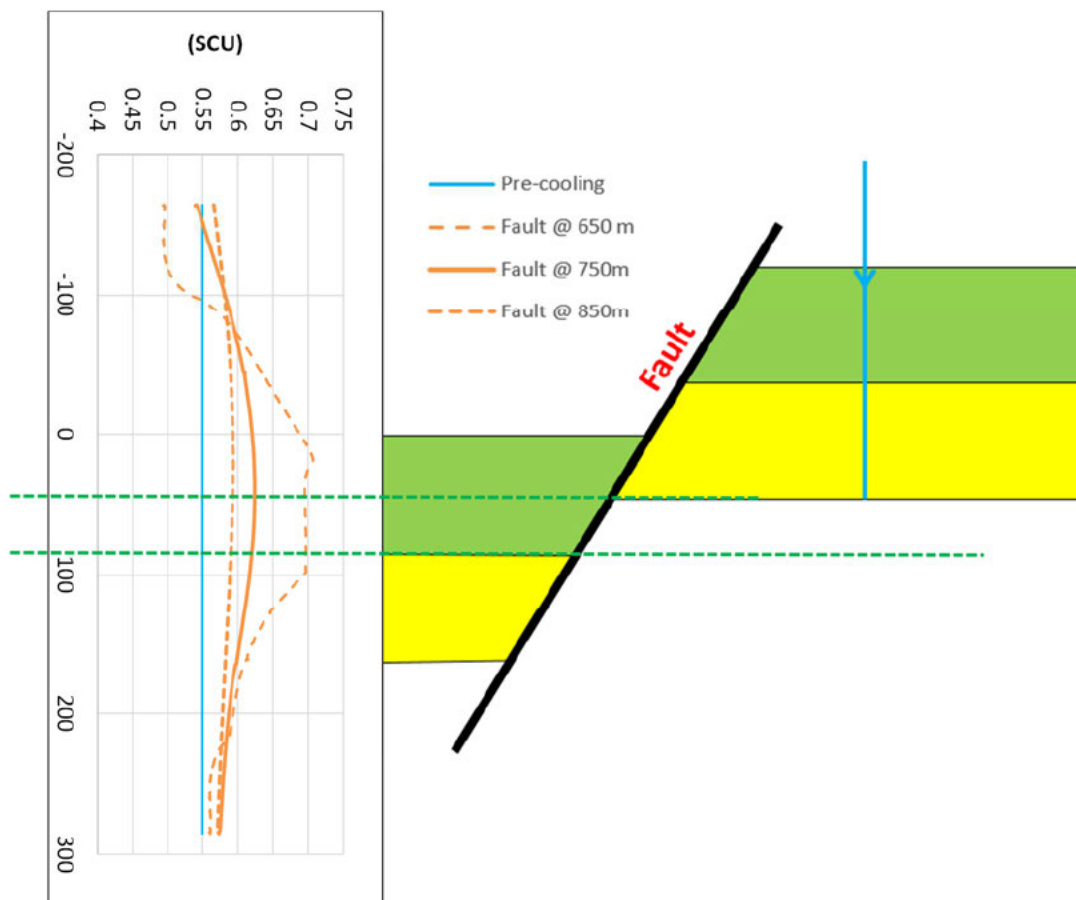


Figure 5-13. Computed SCU along the fault for injection rate 240 m³/hr and permeable Fault 1. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ± 100 m.

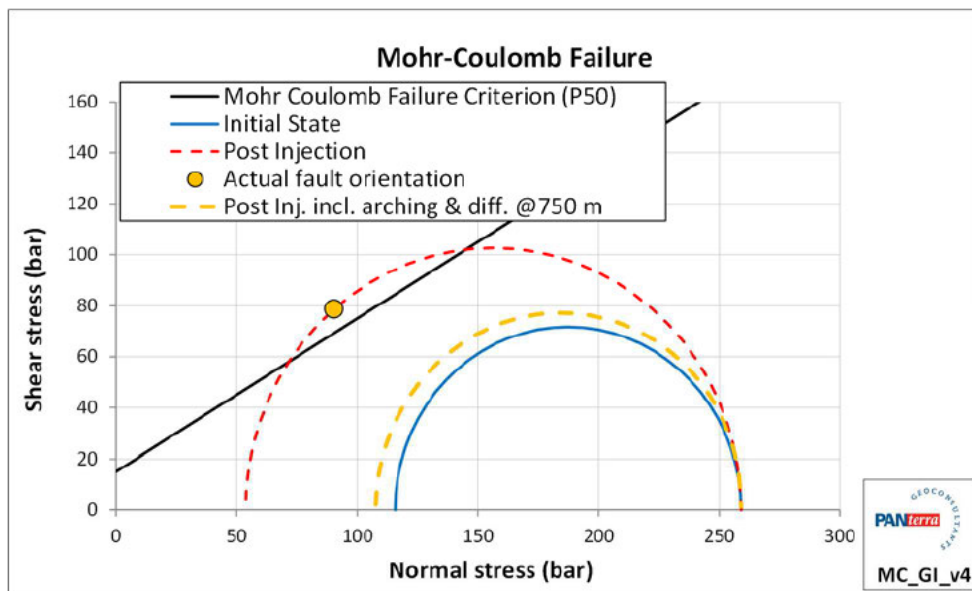


Fig. 5-14 Mohr circles for injection rate 240 m³/hr and permeable Fault 1 at the “worst” point along the fault (see fig. 5-13).

5.1.3.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are the same as for the case of a 344 m³/hr injection rate and shown in Table 5-1 above.

The results of this analysis are shown in Fig. 5-15 Fig. 5-16. The majority of SCU values seen are in the 0.4-0.9 range, with 7% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 10% an SCU > 1 (based on the P90 Mohr-Coulomb failure line).

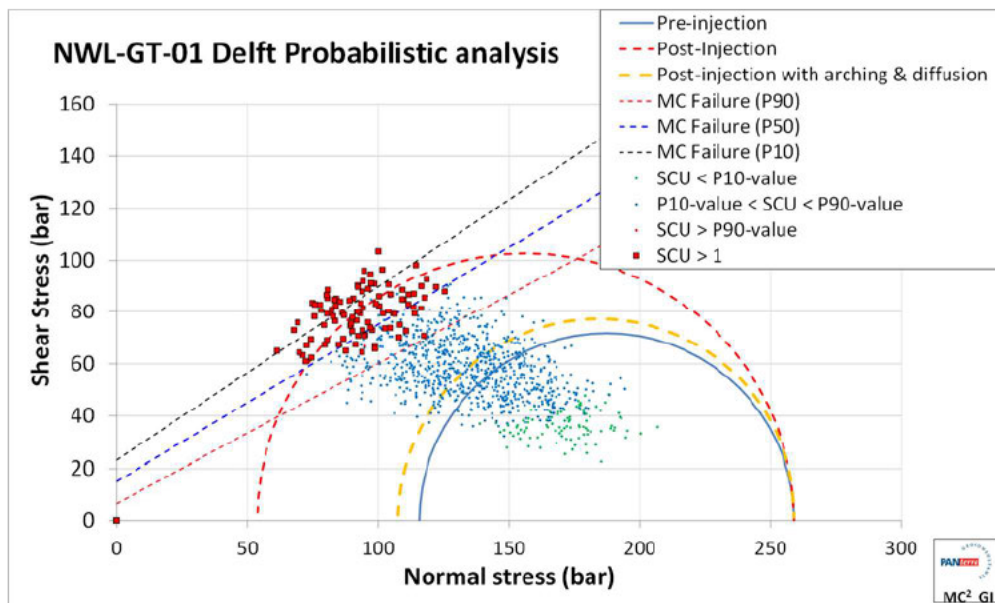


Figure 5-15. Results of Mohr-Coulomb Monte-Carlo for cooling around permeable Fault 1 as a result of injection into well NLW-GT-01, after 30 years of injection at 240 m³/hr. The dots represent the simulations, colours indicating the P10,P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

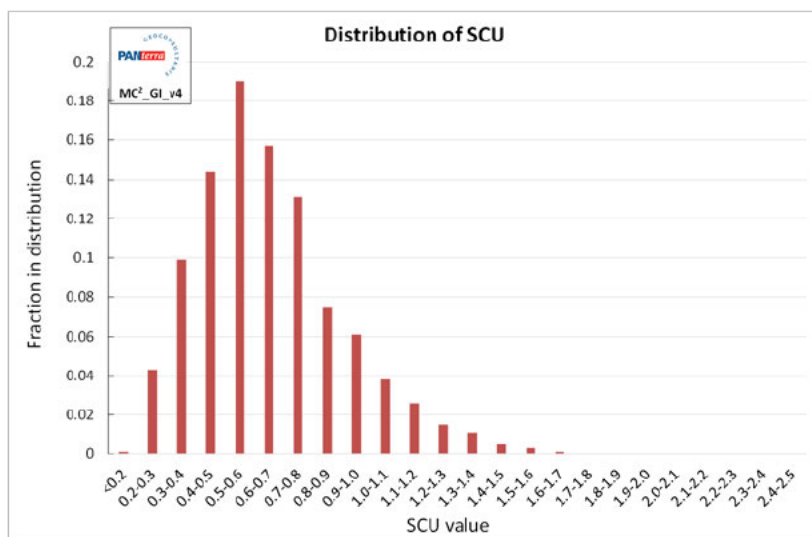


Figure 5-16. Probability diagram of the simulated SCU values after 30 years of injection at 240 m³/hr. Permeable Fault 1. The bulk of the values are in between 0.4 and 0.9, with 7% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 10% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 240 m³/hr, the probability of activation of permeable Fault 1 by injecting 25°C water into the Delft formation via NLW-GT-01 is slightly below that for 344 m³/hr injection into impermeable Fault 1 (20%). This small difference can be explained by the fact that the cold front profiles for both cases are not significantly different (compare Figures 5-12 and 5-7). Below, it will be shown that the results for 240 m³/hr injection and impermeable Fault 1 are almost identical to those for 240 m³/hr injection and permeable Fault 1 as presented above. This is not really surprising as in the latter case, the cold front has hardly penetrated beyond the fault.

5.1.4 Injection rate 240 m³/hr and impermeable Fault 1

5.1.4.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Fig. 5-17 for the case of an impermeable fault at 750 m from the injector. After 30 years of injection we observe a temperature alteration up to ~750 m. For the base case of a fault at 750 m, there is hardly a difference with the case of the permeable fault (Fig. 5-12), because the cold front ends at ~750 m from the injector. Therefore, it is expected that for the base case results are very similar to the permeable fault. Because the scenario of a fault at 650 m from the injector does have some cooling on the other side for a permeable fault, the Monte Carlo results are expected to yield slightly more favorable results than for the permeable fault case.

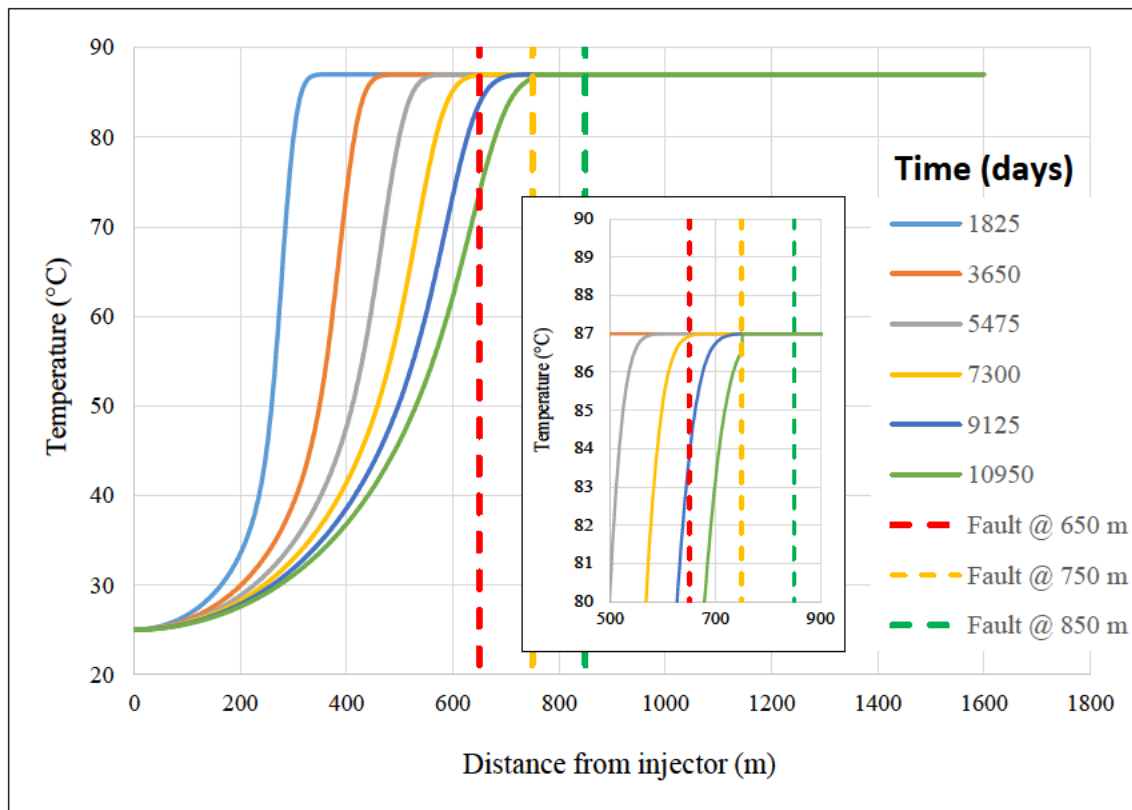
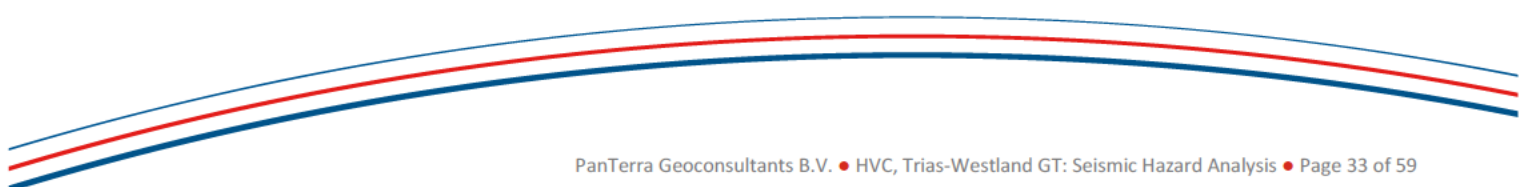


Figure 5-17 Temperature profile in the reservoir away from the injector after 30 years of 240 m³/hr injection for the case of a impermeable Fault 1 at 750 m from the injector. Because for the bases case, the thermal front ends at about 750 m from the injector, there is only a small difference with the permeable fault for injector-fault distance of 750 m (see inset).

5.1.4.2 Deterministic analysis

Results are given in Fig. 5-18, where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 240 m³/hr. It should be noted that only for the case of a fault at 650m from the injector, the SU-profile differs from that in figure 5-13, in line with expectations (see discussion above). Therefore, the maximum SCU for the base case is the same as for the permeable fault case (SCU = 0.62). Varying the fault distance over ± 100 m with respect to base case of 750 m from injector results in an SCU-variation between 0.59 and 0.71.

Figure 5-19 shows a deterministic failure analysis for the “worst” point on the SCU curve of Figure 5-18. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 240 m³/hr for an impermeable fault at 750 m. Because this shows the situation for the base case of injector-fault distance of 750m, the results of Fig. 5-19 are (almost) identical to those of Fig. 5-14.



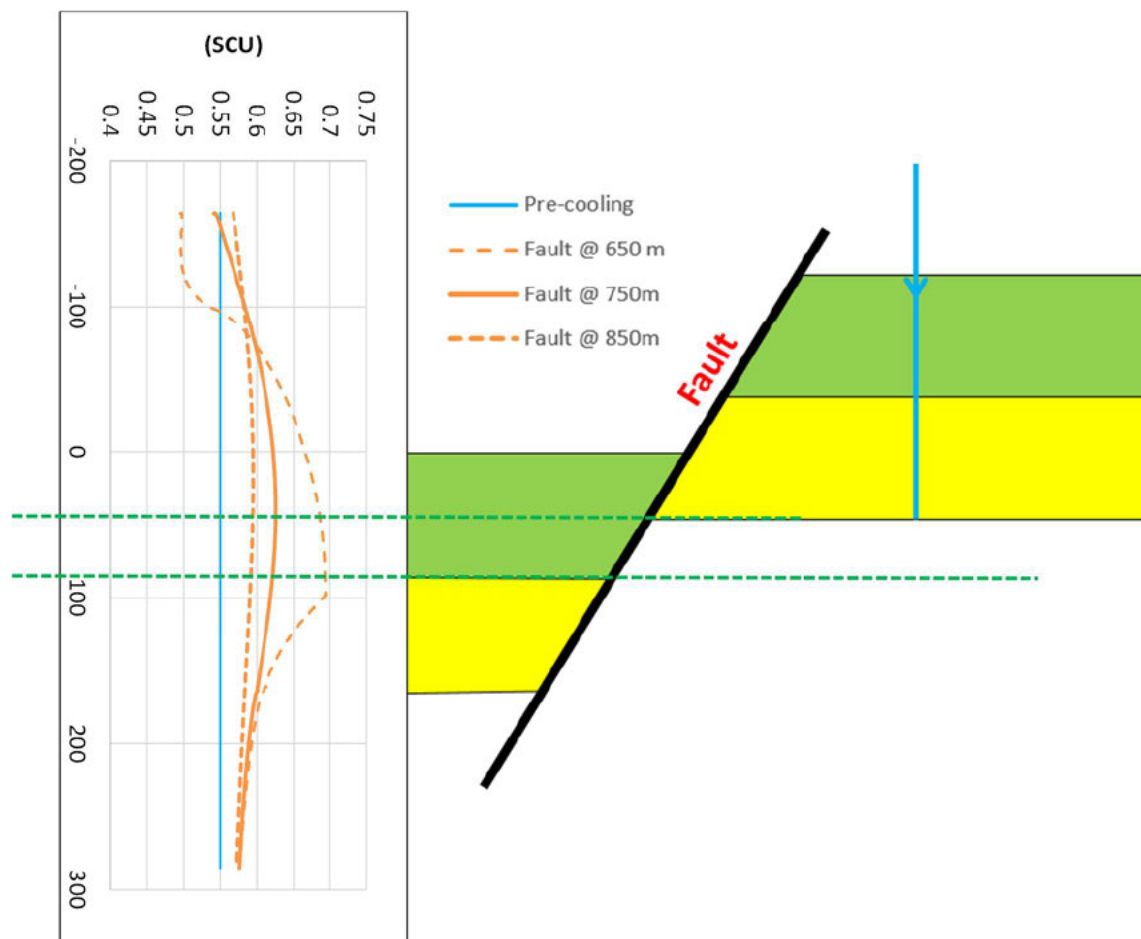


Figure 5-18. Computed SCU along the fault for injection rate 240 m³/hr and impermeable Fault 1. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ±100m.

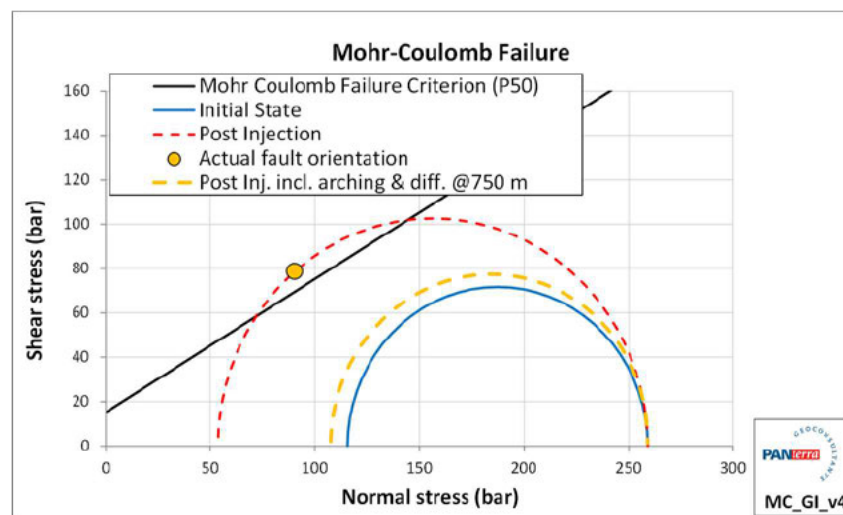


Fig. 5-19 Mohr circles for injection rate 240 m³/hr and impermeable Fault 1 at the “worst” point along the fault (see fig. 5-18).

5.1.4.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are the same as for the case of a 344 m³/hr injection rate and shown in Table 5-1 above.

The results of this analysis are shown in Fig. 5-20 and Fig. 5-21. The majority of SCU values seen are in the 0.4-0.9 range, with 7% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 10% an SCU > 1 (based on the P90 Mohr-Coulomb failure line). This is more or less identical to the permeable fault, although one would expect a little more arching for the case of nearby fault (650 m) owing to (a bit) more arching, but apparently this difference is very small.

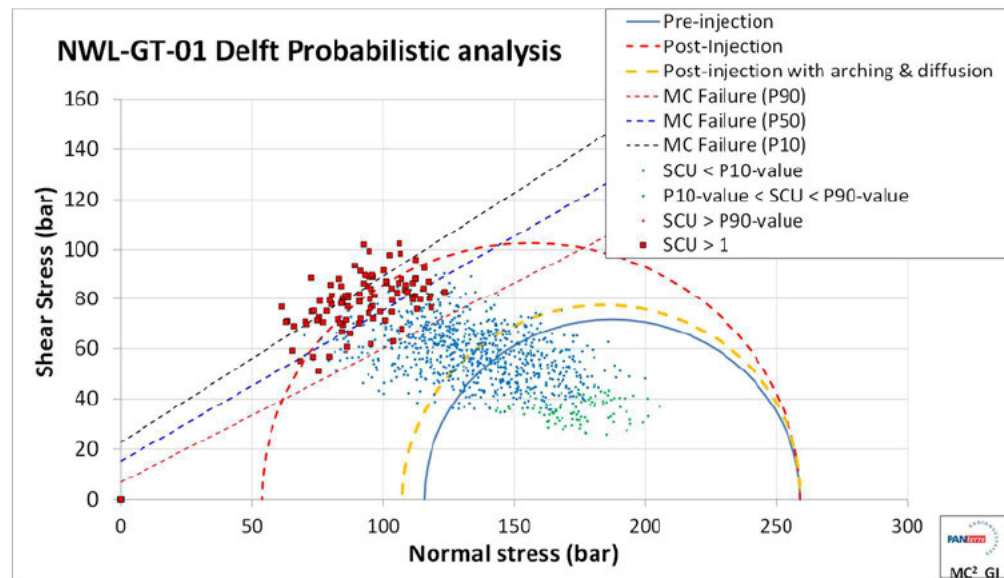


Figure 5-20. Results of Mohr-Coulomb Monte-Carlo for cooling around impermeable Fault 1 as a result of injection into well NLW-GT-01, after 30 years of injection at 240 m³/hr. The dots represent the simulations, colours indicating the P10,P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

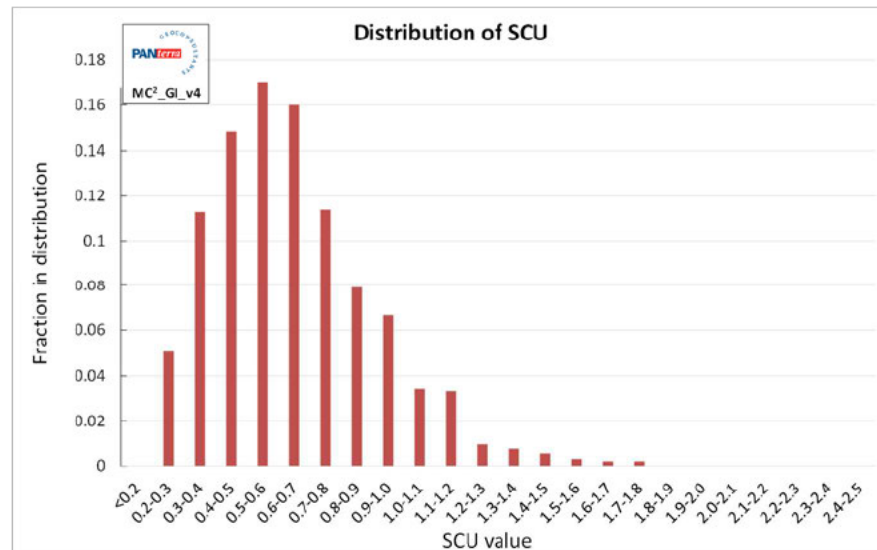


Figure 5-21. Probability diagram of the simulated SCU values after 30 years of injection at 240 m³/hr. Permeable Fault 1. The bulk of the values are in between 0.4 and 0.9, with 7% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 10% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 240 m³/hr, the probability of activation of impermeable Fault 1 by injecting 25°C water into the Delft formation via NLW-GT-01 is more or less the same as the probability of activation of permeable Fault 1 under the same circumstances.

5.2 Injector well NLW-GT-04 – injection into the Delft formation – Fault 2

Results of Fault 2 stability will be presented for two different injection rates: 400 m³/hr @ 80% uptime (effectively 320 m³/hr) and 300 m³/hr @ 80% uptime (effectively 240 m³/hr). For both injection rates, results will be presented for a permeable Fault 2 and an impermeable Fault 2.

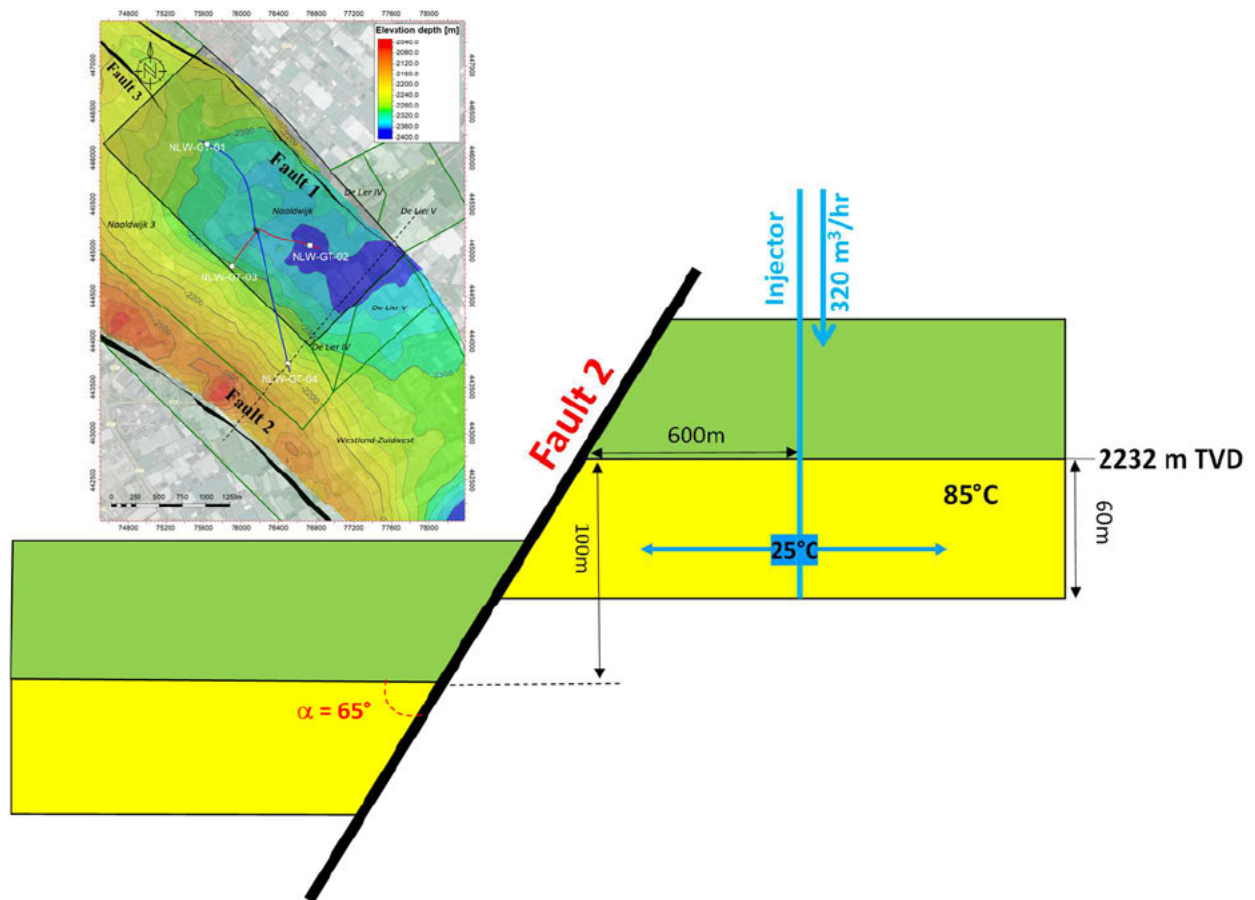


Figure 5-22 NLW-GT-04 Delft Fault 2: top view and side view (cross section) of injector and fault 2 along the dashed line indicated in the top view.

5.2.1 Injection rate 320 m³/hr and permeable Fault 2

5.2.1.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Fig. 5-23. The cooled zone is not an abrupt front but rather influenced by thermal diffusion, both within the reservoir and from the cap- and baserock into the reservoir.

After 30 years of injection we observe a temperature alteration up to ~950 m. This is considered the cold water “front”. Fault 2 is expected at 600 m. This scenario is schematically depicted in Fig. 5-22.

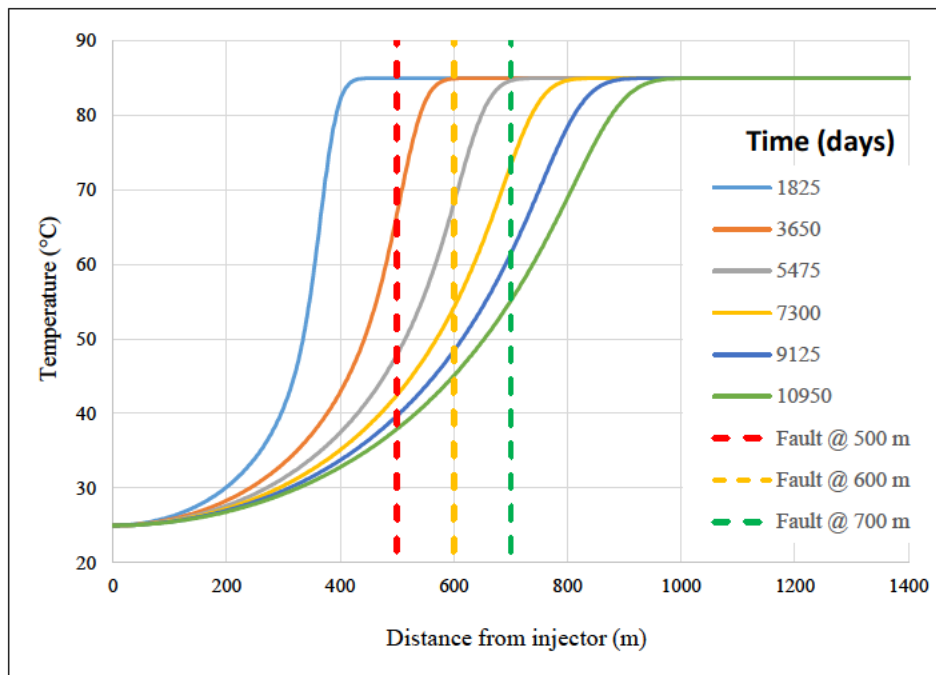


Figure 5-23 Temperature profile in the reservoir away from the injector after 30 years of injection of 320 m³/hr for a permeable Fault 2.

5.2.1.2 Deterministic analysis

The methodology as described in Section 3.1 is applied to estimate the impact of the cooling on the Shear Capacity Utilisation (SCU). In order to take into account the effect of partial cooling, the entire temperature profile in the cooled zones to the left and to the right of the fault is computed. Subsequently, the thermo-elastic stress change on the fault resulting from this temperature profile is calculated. As a fault position is a matter of interpretation and faults often display 'damage zones' an uncertainty was taken into account in the fault position of ± 100 m.

The results are given in Fig. 5-24, where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 320 m³/hr. As can be seen, the maximum SCU for the base case (at vertical coordinate $x \approx 40$ -50 m) is around 0.99 which is on the border of fault reactivation. Varying the fault distance over ± 100 m with respect to base case of 600 m from injector results in an SCU-variation between 0.85 and 1.06. These SCU-values are significantly higher than obtained for Fault 1 as a result of injection at similar rates from NLW-GT-01. The main reason for this difference is that NLW-GT-04 is closer to Fault 2 than NLW-GT-01 is to Fault 1.

Figure 5-25 shows a deterministic failure analysis for the "worst" point on the SCU curve of Fig. 5-24. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 320 m³/hr for a permeable fault at 600 m. The red dashed Mohr circle is obtained by assuming a uniform cooling down to the injection temperature of 25°C across the entire reservoir. The yellow dashed Mohr circle includes the actual change of state of stress as a result of the cooled area, i.e. it includes the impact of stress arching by uncooled areas further away from the injector. Also, the approach presented here includes the impact of stress concentrations along the fault.

It should be noted that the impact of stress arching is very limited in this case (Fig. 5-25), contrary to the case of Fault 1 and injection from NLW-GT-01 (Fig. 5-4). This can be explained by the fact that in the current

case (Fault 4) the lateral extent of the cooled zone on the other side of the fault is fairly large compared to the reservoir thickness. As will be shown below, for lower injection rates, the cooled area within the reservoir will be smaller, resulting in a higher degree of arching, in line with expectations.

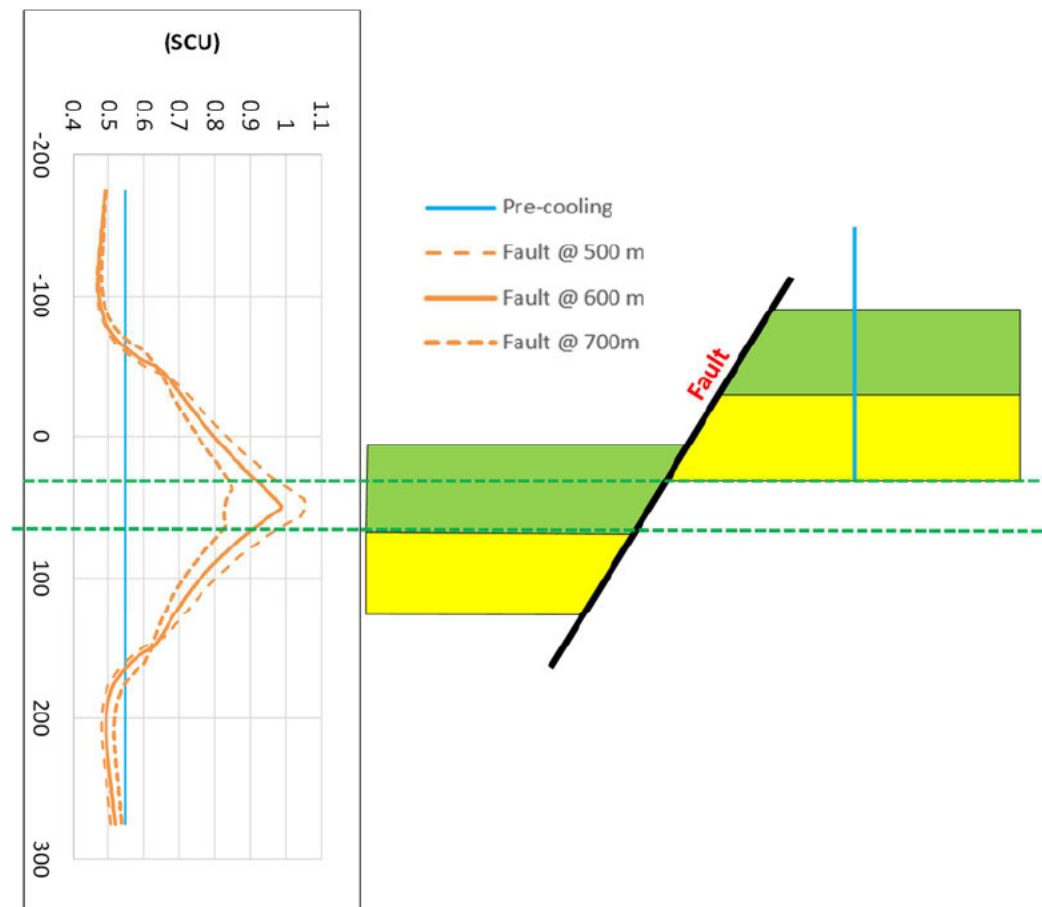


Figure 5-24 Computed SCU along the fault for injection rate 320 m³/hr and permeable Fault 2. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ±100m.

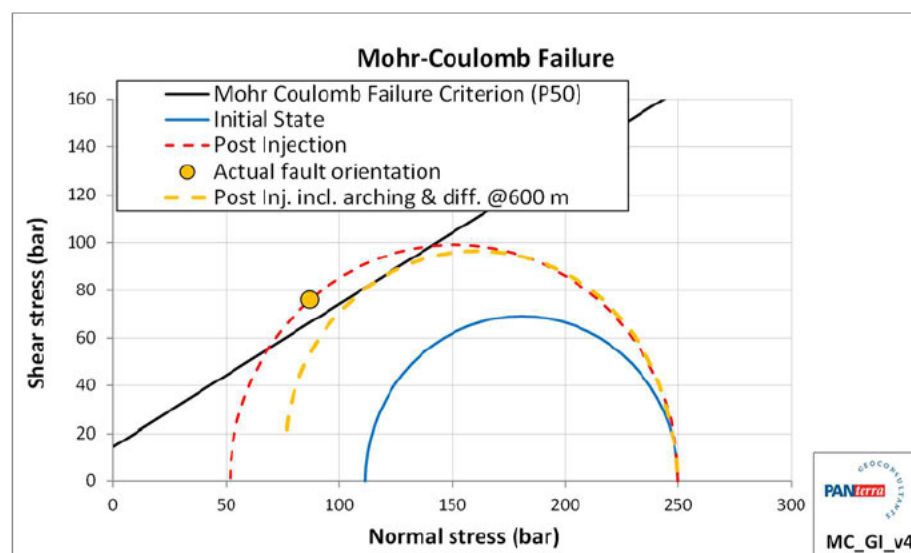


Figure 5-25 Mohr circles for injection rate 320 m³/hr and permeable Fault 2 at the “worst” point along the fault (see fig. 5-24).

5.2.1.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are shown in Table 5-1, which displays the input parameters for the probabilistic analysis of the Delft formation and Fault 2, including their low-med-high values. The parameters and reasoning have been discussed in section 4.3.

Table 5-2 Input parameters for probabilistic analysis of the Delft formation and Fault 2. See text for discussion.

	Parameter	Min	Median	Max
Rock Parameters	Reservoir Temperature (°C)	82	85	88
	Thermoelastic coefficient (bar/°C)	0.5	1.0	1.5
	Vertical stress gradient (bar/m)	0.21	0.22	0.23
	Horizontal stress gradient (bar/m)	0.144	0.158	0.189
Fault Parameters	Cohesion (bar)	0	15	30
	Friction coefficient (-)	0.48	0.60	0.72
	Dip (degrees)	55	65	75
	Distance from injector (m)	500	600	700

The results of this analysis are shown in Fig. 5-26 and Fig. 5-27. The majority of SCU values seen are in the 0.4-0.9 range, with 7% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 20% an SCU > 1 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 320 m³/hr, the probability of activation of a permeable Fault 2 by injecting 25°C water into the Delft formation via NLW-GT-02 could be considered “medium”.

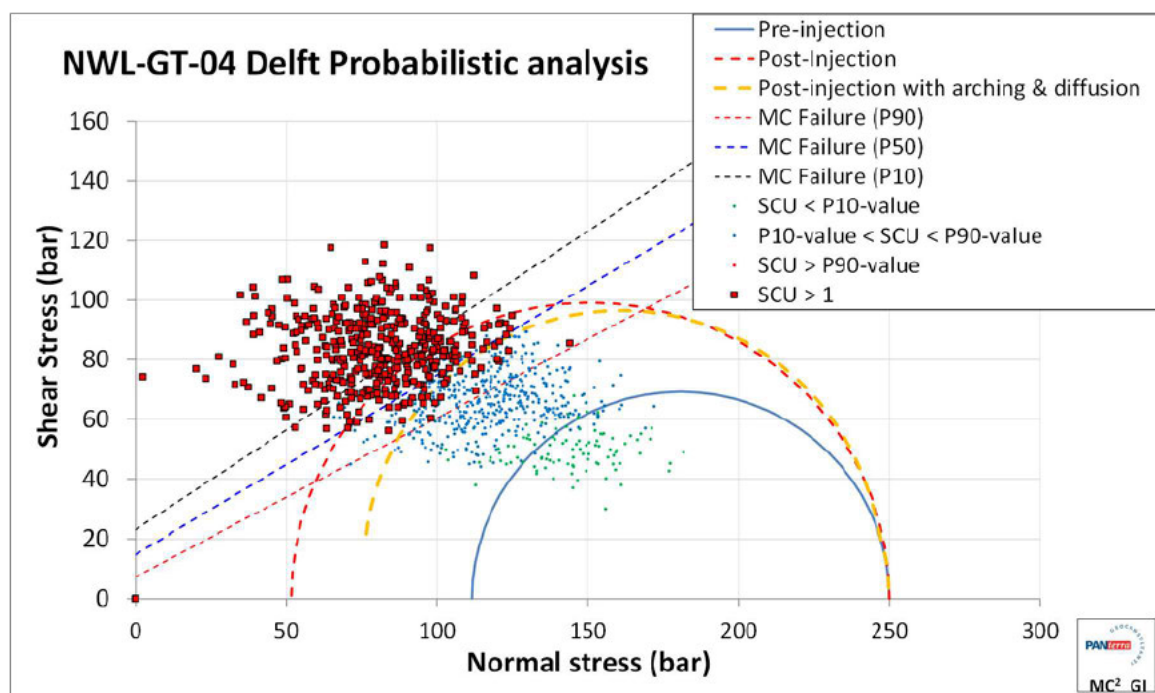


Figure 5-26 Results of Mohr-Coulomb Monte-Carlo for cooling around a permeable Fault 2 as a result of injection into injector NLW-GT-04, after 30 years of injection at 320 m³/hr. The dots represent the simulations, colours indicating the P10,P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

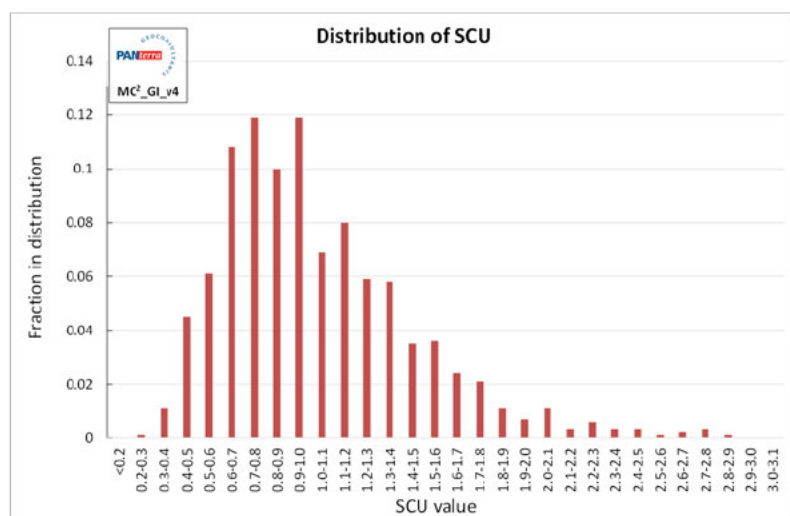
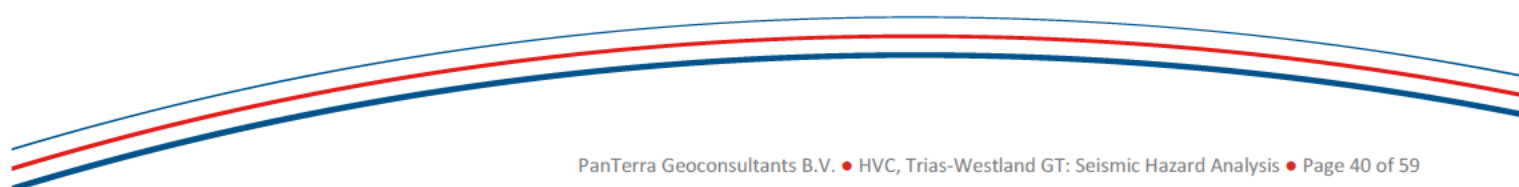


Figure 5-27. Probability diagram of the simulated SCU values after 30 years of injection at 320 m³/hr. Pemeable Fault 2. The bulk of the values are in between 0.4 and 0.9, with 12% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 44% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

5.2.2 Injection rate 320 m³/hr and impermeable Fault 2

5.2.2.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Fig. 5-28 for the case of an impermeable fault at 750 m from the injector. In this case, the flood front (and therefore cold front) does not penetrate beyond the fault.



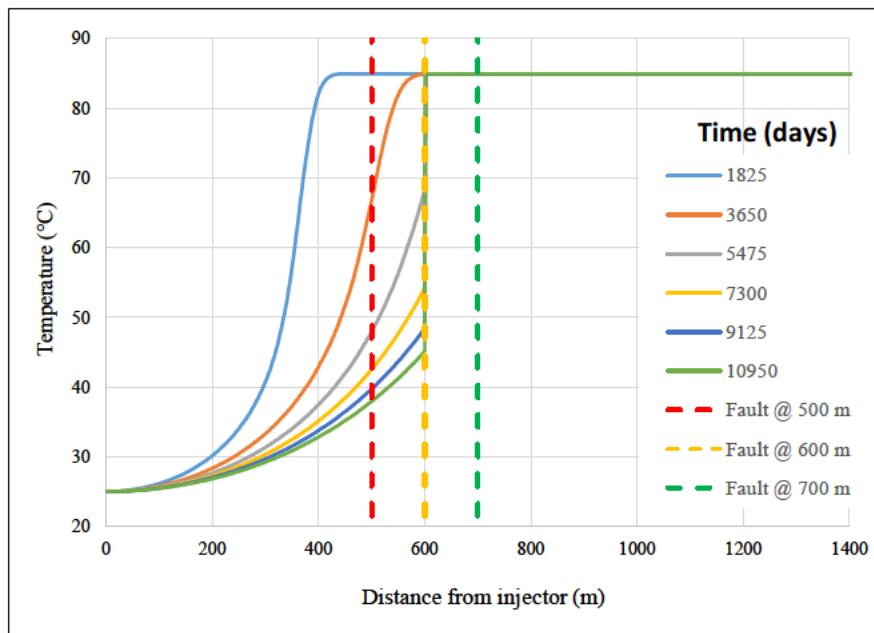


Figure 5-28 Temperature profile in the reservoir away from the injector after 30 years of injection of 320 m³/hr for the case of an impermeable Fault 2 at 600 m from the injector.

5.2.2.2 Deterministic analysis

Results are given in Fig. 5-29 where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 320 m³/hr. As can be seen, the maximum SCU for the base case (at vertical coordinate $x \approx 50$ m) is around 0.80 which is still significantly below 1. Varying the fault distance over ± 100 m with respect to base case of 600 m from injector results in an SCU-variation between 0.76 and 0.82.

Fig. 5-30 shows a deterministic failure analysis for the “worst” point on the SCU curve of Fig. 5-29. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 320 m³/hr for an impermeable fault at 600 m. The impact of stress arching is significantly more pronounced in this case (Figure 5-30) than in the case of a permeable fault (Fig. 5-25), as can be seen from the smaller dashed yellow Mohr-Coulomb circle. This large difference can be explained by the fact that in this case the cooled zone has not extended beyond the fault, whereas for a permeable fault, it has extended by ~350m beyond the fault.

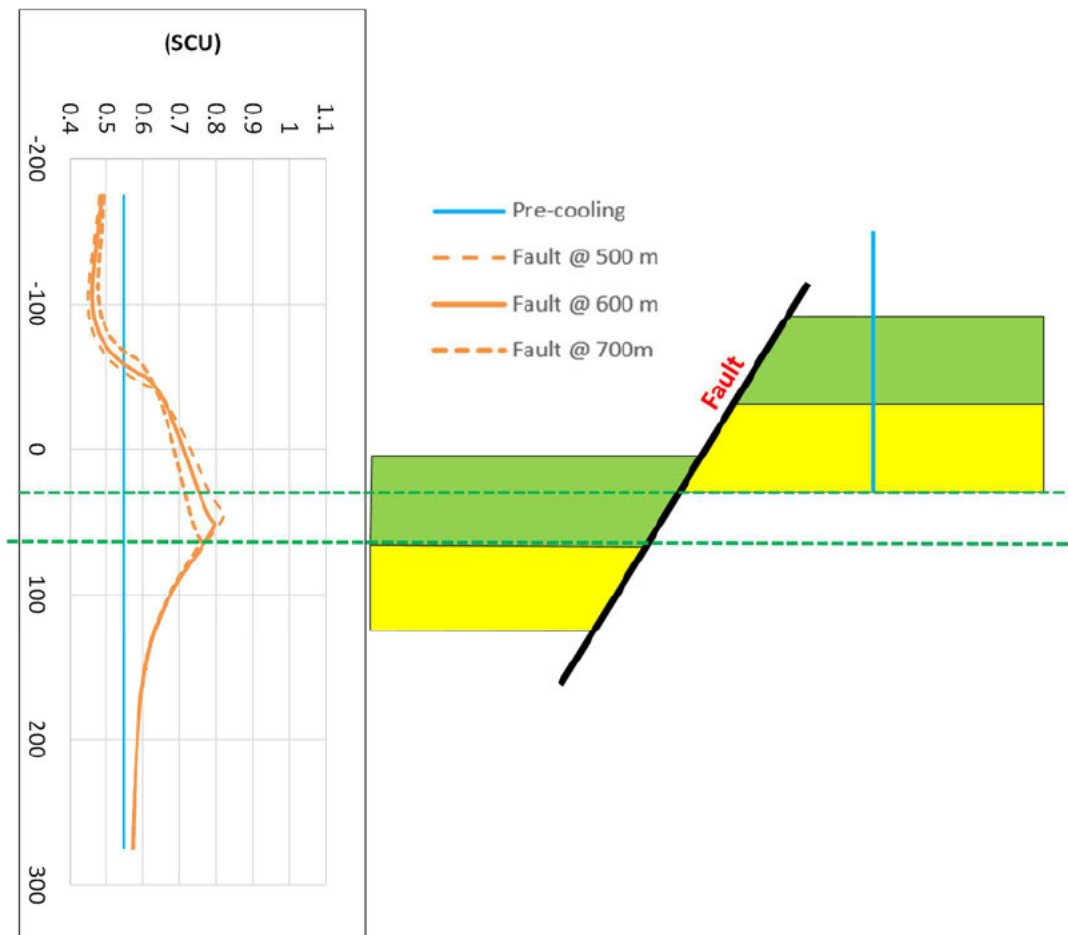


Figure 5-29 Computed SCU along the fault for injection rate 320 m³/hr and impermeable Fault 2. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ± 100 m.

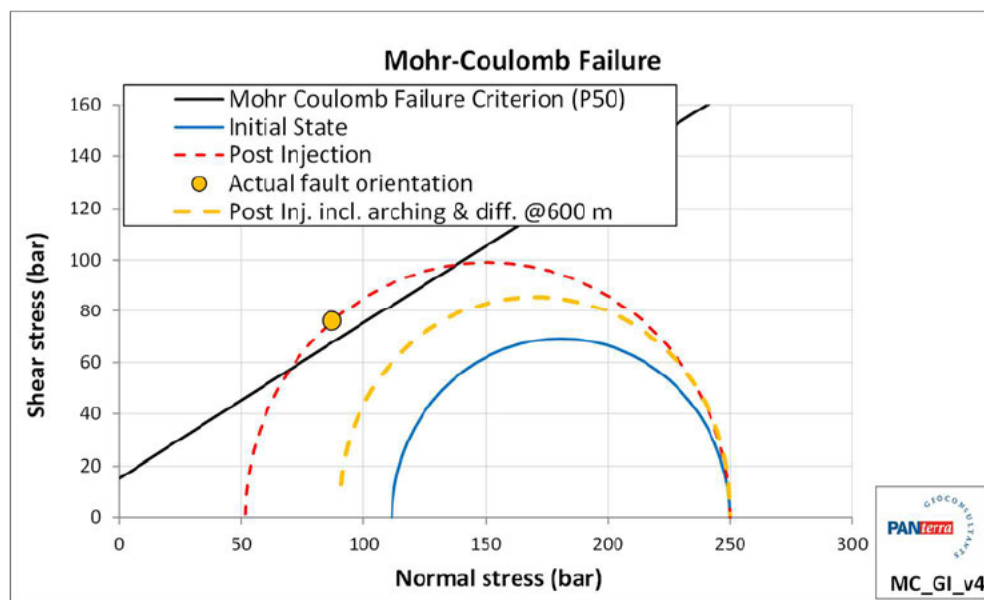


Fig. 5-30 Mohr circles for injection rate 320 m³/hr and impermeable Fault 2 at the “worst” point along the fault (see fig. 5-29).

5.2.2.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are the same as for the case of a permeable fault and shown in Table 5-1 above.

The results of this analysis are shown Fig. 5-31 and Fig. 5-32. The majority of SCU values seen are in the 0.4-0.9 range, with 8% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 20% an SCU > 1 (based on the P90 Mohr-Coulomb failure line). These percentages are significantly lower than those for a permeable Fault 2.

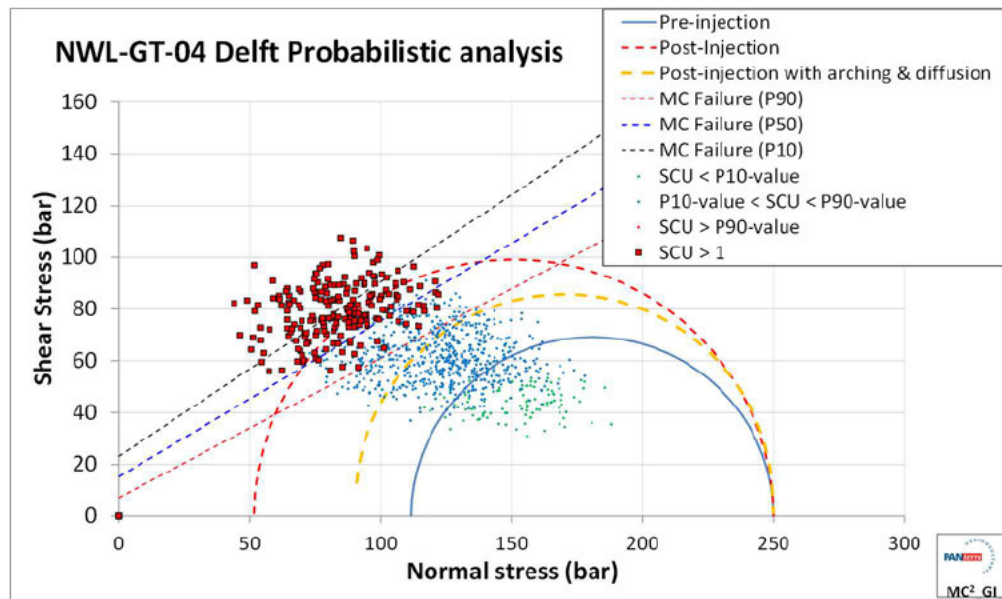


Figure 5-31 Results of Mohr-Coulomb Monte-Carlo for cooling around impermeable Fault 4 as a result of injection into NLW-GT-04, after 30 years of injection at 344 m³/hr. The dots represent the simulations, colours indicating the P10, P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

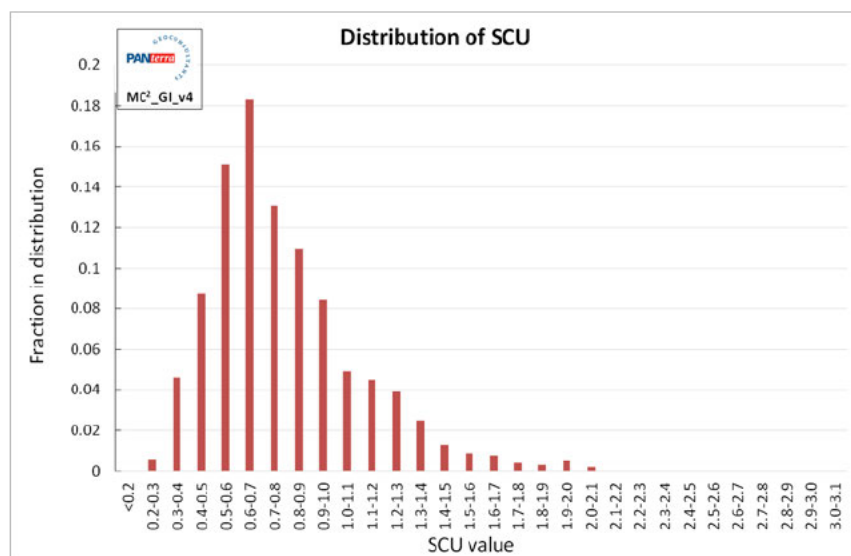


Figure 5-32. Probability diagram of the simulated SCU values after 30 years of injection at 320 m³/hr. Impermeable Fault 2. The bulk of the values are in between 0.4 and 0.9, with 8% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 20% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 320 m³/hr, the probability of activation of Fault 2 by injecting 25°C water into the Delft formation via NLW-GT-02 can be considered non-negligible. However, the probability of fault activation for an impermeable Fault 2 (20%) is significantly below that for a permeable Fault 2 (44%). This large difference can be explained by the fact that for a permeable Fault 2, the cold front after 30 years of injection has penetrated significantly into the part of the reservoir beyond the fault (refer to Figure 5-23).

5.2.3 Injection rate 240 m³/hr and permeable Fault 2

5.2.3.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Fig. 5-33 for the case of a permeable fault at 600 m from the injector. After 30 years of injection we observe a temperature alteration up to ~800-850 m.

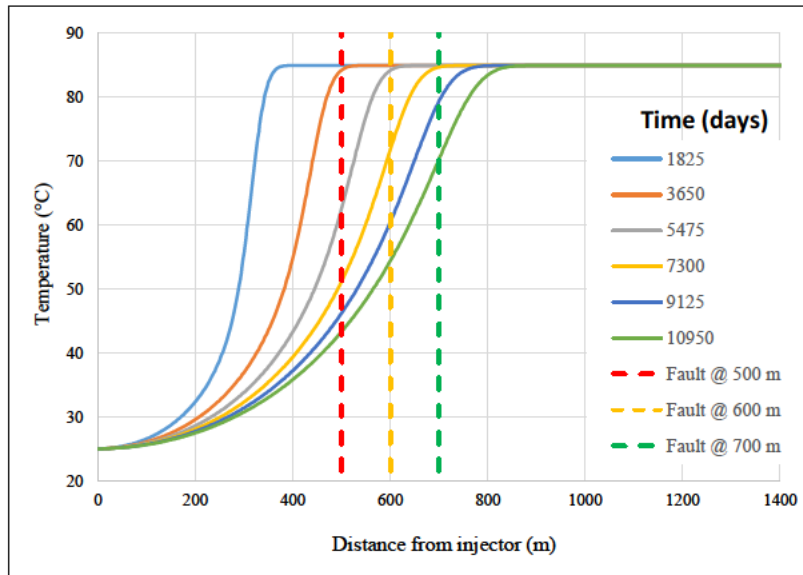


Figure 5-33 Temperature profile in the reservoir away from the injector after 30 years of 240 m³/hr injection for the case of a permeable Fault 2 at 600 m from the injector.

5.2.3.2 Deterministic analysis

Results are given in Fig. 5-34 where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 240 m³/hr. As can be seen, the maximum SCU for the base case (at vertical coordinate $x \approx 30$ m) is around 0.85 which is still below 1. Varying the fault distance over ± 100 m with respect to base case of 600 m from injector results in an SCU-variation between 0.70 and 1.01.

Fig. 5-35 shows a deterministic failure analysis for the “worst” point on the SCU curve of Fig. 5-34. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 240 m³/hr for a permeable fault at 600 m. The impact of stress arching is more pronounced in this case (Figure 5-35) than in the case of 320 m³/hr and permeable fault (Fig. 5-25), as can be seen from the smaller dashed yellow Mohr-Coulomb circle. This can be explained by the fact that in this case the cold zone has not yet penetrated as far beyond the fault as in the case of 320 m³/hr. However, it should be noted that for 320 m³/hr injection and impermeable Fault 2 (Fig. 5-30), arching is stronger than for 240 m³/hr and permeable Fault 2 (Fig. 5-35). This clearly demonstrates the significant impact of fault permeability on fault reactivation for the case of Fault 2.

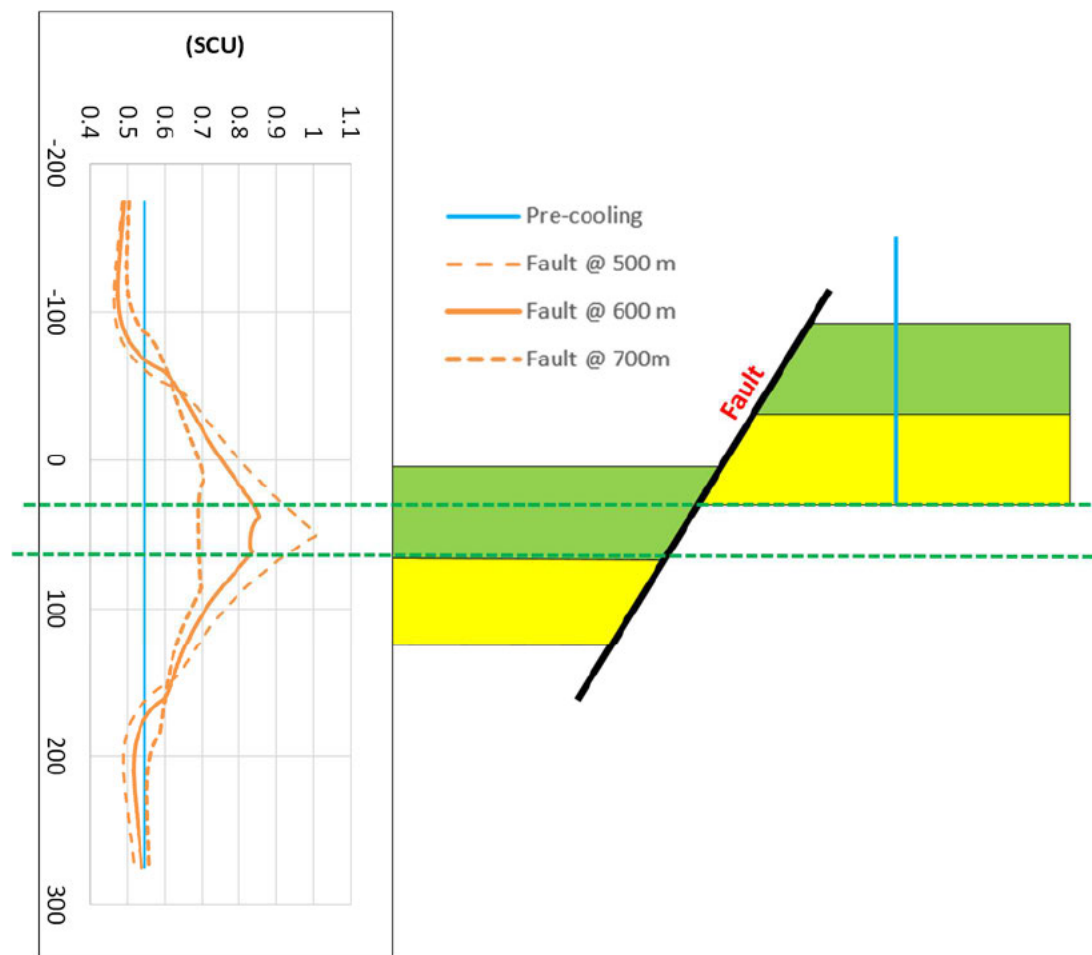


Figure 5-34. Computed SCU along the fault for injection rate 240 m³/hr and permeable Fault 2. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ±100m.

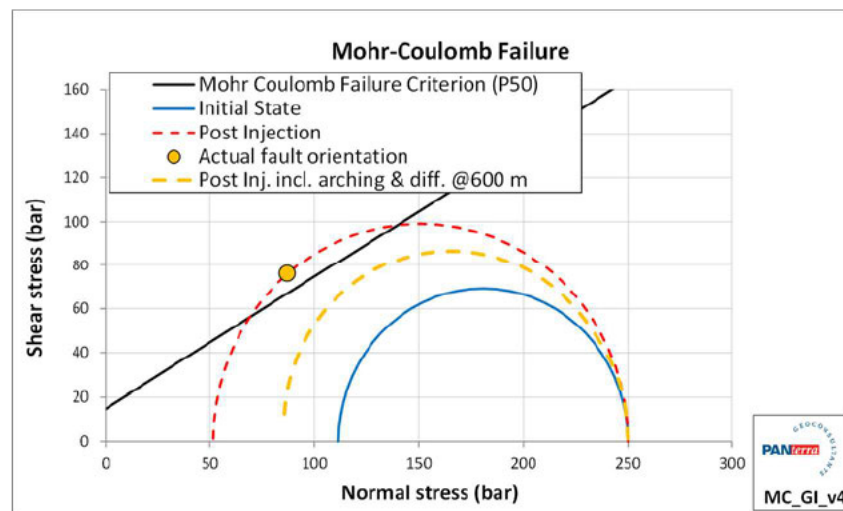


Fig. 5-35 Mohr circles for injection rate 240 m³/hr and permeable Fault 2 at the “worst” point along the fault (see fig. 5-34).

5.2.3.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are the same as for the case of a 320 m³/hr injection rate and shown in Table 5-1 above.

The results of this analysis are shown in Fig. 5-36 and Fig. 5-37. The majority of SCU values seen are in the 0.4-0.9 range, with 10% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 29% an SCU > 1 (based on the P90 Mohr-Coulomb failure line).

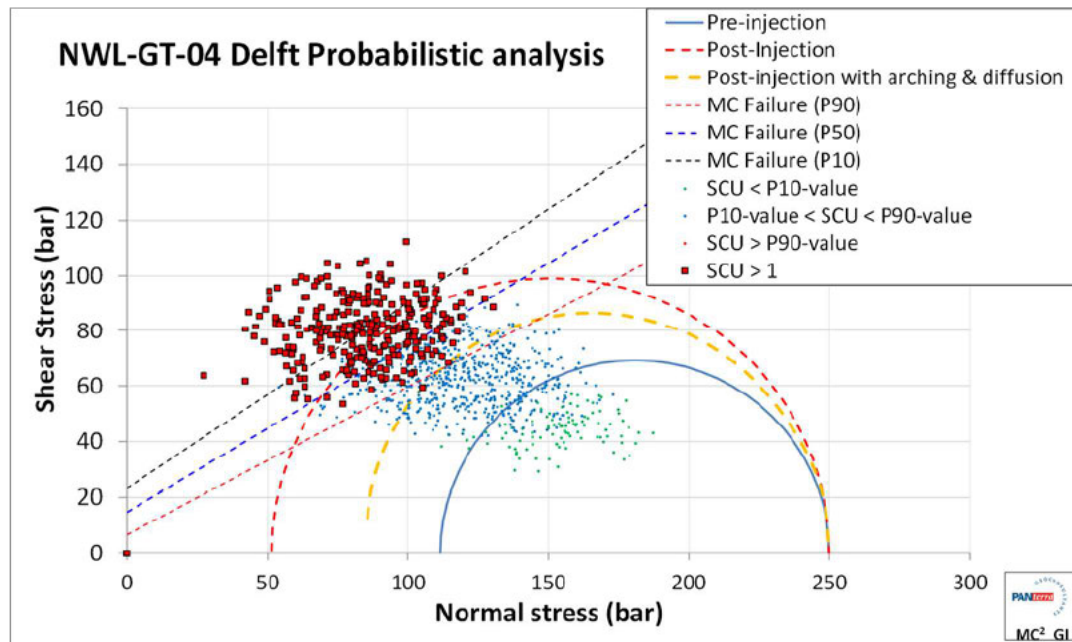


Figure 5-36. Results of Mohr-Coulomb Monte-Carlo for cooling around permeable Fault 2 as a result of injection into NLW-GT-04, after 30 years of injection at 240 m³/hr. The dots represent the simulations, colours indicating the P10,P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

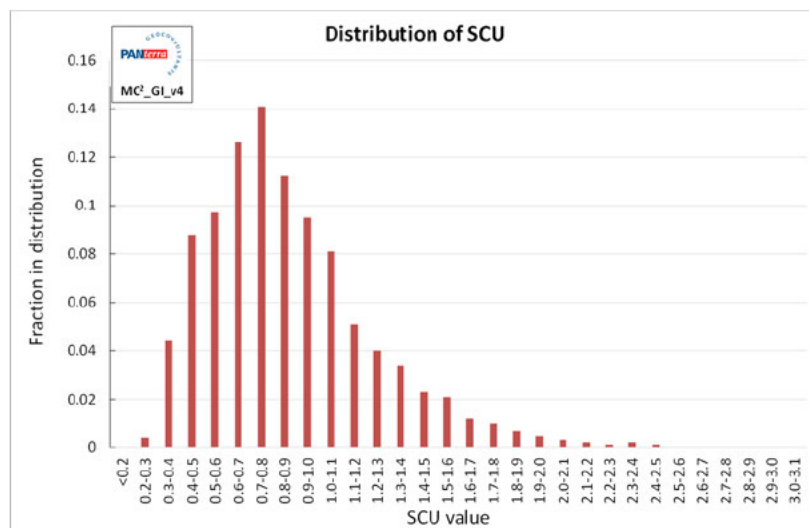


Figure 5-37. Probability diagram of the simulated SCU values after 30 years of injection at 240 m³/hr. Permeable Fault 2. The bulk of the values are in between 0.4 and 0.9, with 10% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 29% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 240 m³/hr, the probability of activation of permeable Fault 2 by injecting 25°C water into the Delft formation via NLW-GT-02 is “non-negligible” to medium. It should be noted that the probability of fault reactivation (~30%) in this case is higher than the probability of fault reactivation (~20%) for 320 m³/hr injection and impermeable Fault 2.

5.2.4 Injection rate 240 m³/hr and impermeable Fault 2

5.2.4.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in Fig. 5-38 for the case of an impermeable fault at 600 m from the injector. In this case, the flood front (and therefore cold front) does not penetrate beyond the fault.

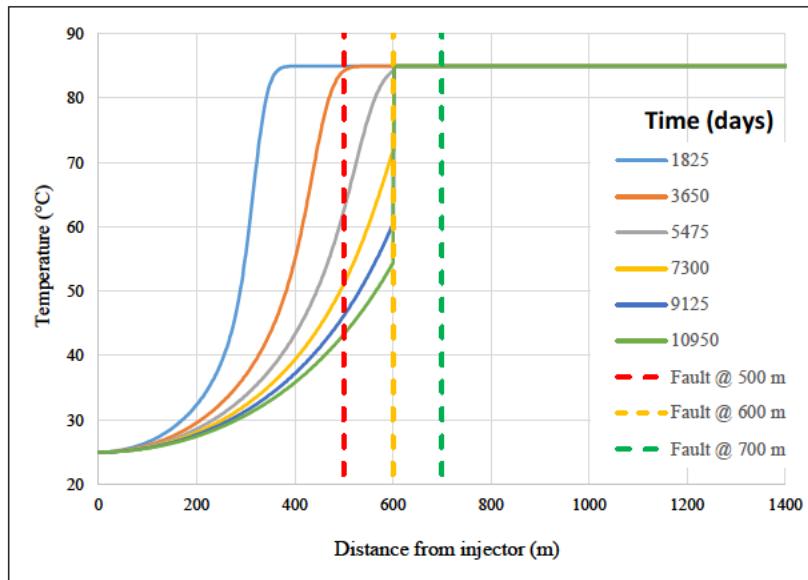
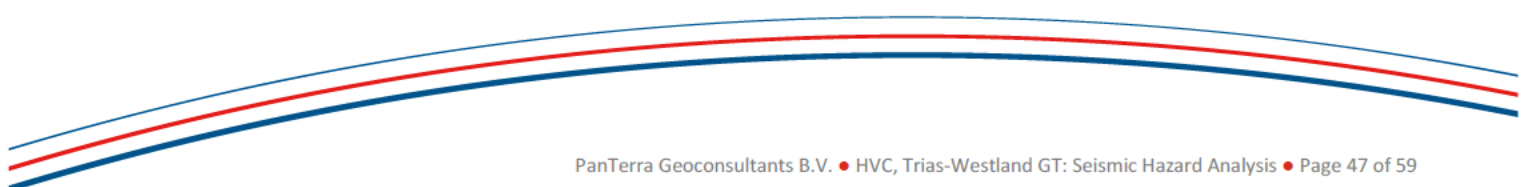


Figure 5-38 Temperature profile in the reservoir away from the injector after 30 years of 240 m³/hr injection for the case of an impermeable Fault 2 at 600 m from the injector.

5.2.4.2 Deterministic analysis

Results are given in Fig. 5-39 where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 240 m³/hr. The maximum SCU for the base case is equal to 0.76. Varying the fault distance over ± 100 m with respect to base case of 600 m from injector results in an SCU-variation between 0.69 and 0.80.

Fig. 5-40 shows a deterministic failure analysis for the “worst” point on the SCU curve of fig. 5-39. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 240 m³/hr for an impermeable fault at 600 m. As can be seen, arching in this case (Fig. 5-40) is slightly more favorable than for the case of a permeable fault and same injection rate (Fig. 5-35), in line with expectations.



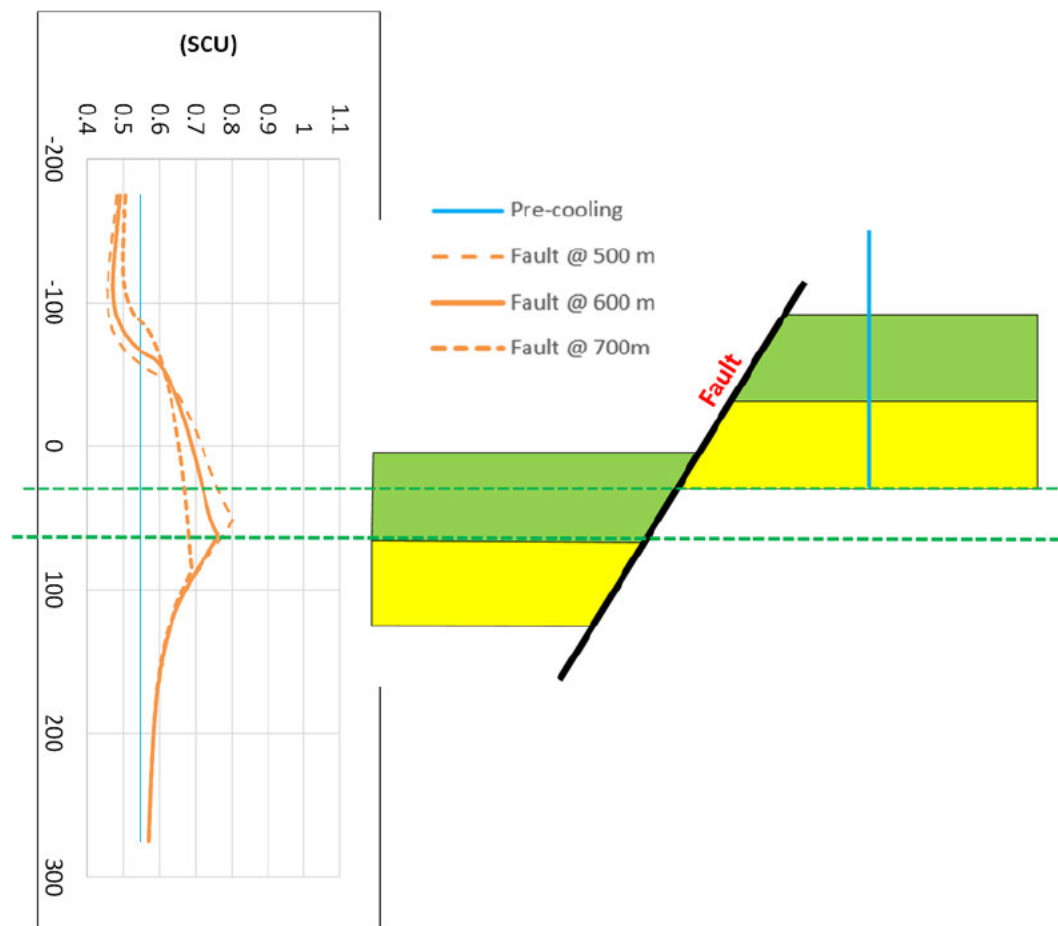


Figure 5-39. Computed SCU along the fault for injection rate 240 m³/hr and impermeable Fault 2. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ±100m.

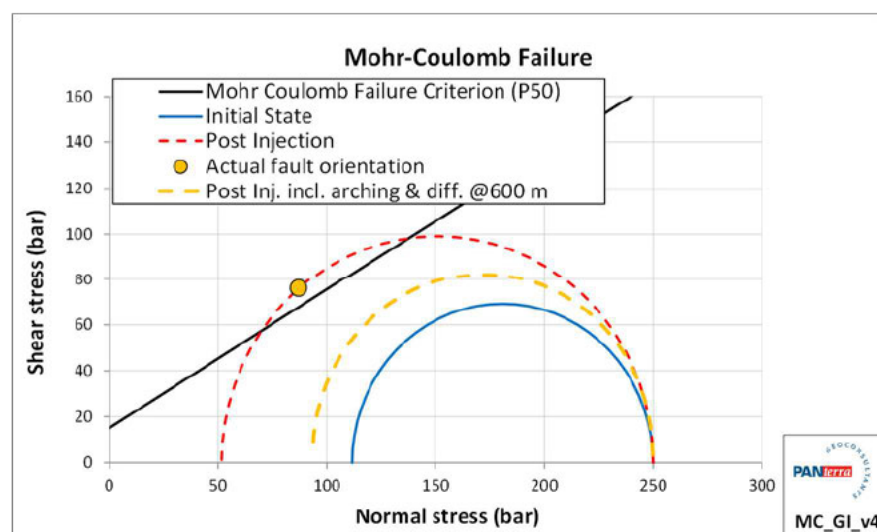


Fig. 5-40 Mohr circles for injection rate 240 m³/hr and impermeable Fault 2 at the “worst” point along the fault (see fig. 5-39).

5.2.4.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are the same as for the case of a 320 m³/hr injection rate and shown in Table 5-1 above.

The results of this analysis are shown in Fig. 5-41 and Fig. 5-42. The majority of SCU values seen are in the 0.4-0.9 range, with 8% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 18% an SCU > 1 (based on the P90 Mohr-Coulomb failure line). This somewhat less than the permeable fault (18% versus 29% probability of reactivation). However, it should be noted that the probability for reactivation for an impermeable Fault 2 are very similar for 30 yrs @ 240 m³/hr and 30 @ 320 m³/hr.

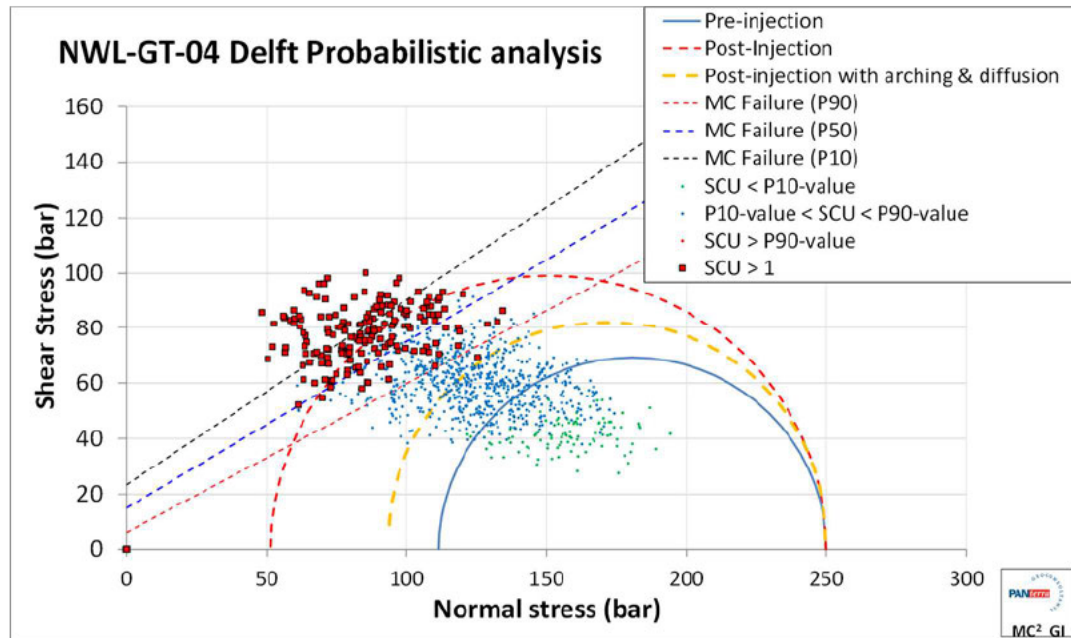


Figure 5-41. Results of Mohr-Coulomb Monte-Carlo for cooling around impermeable Fault 2 as a result of doublet NLW-GT-04, after 30 years of injection at 240 m³/hr. The dots represent the simulations, colours indicating the P10,P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

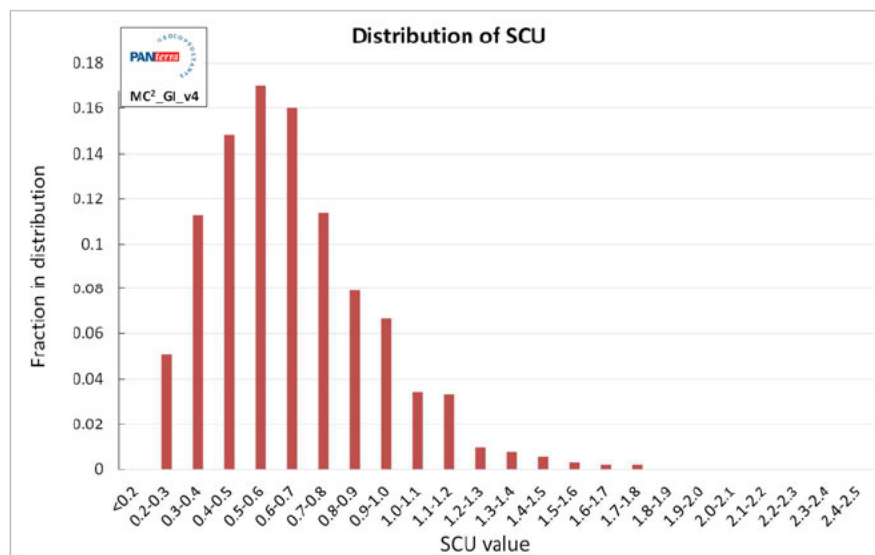
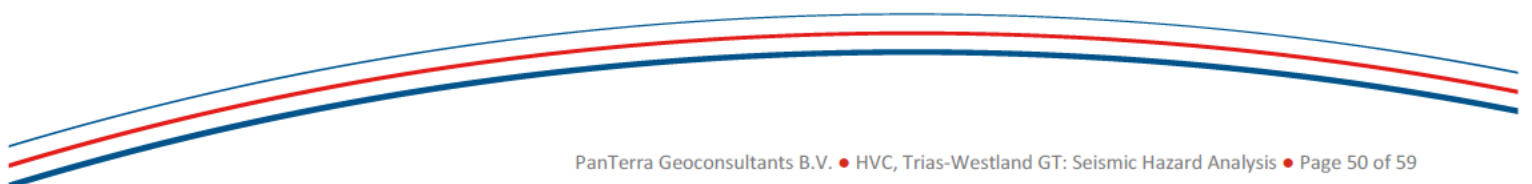


Figure 5-42. Probability diagram of the simulated SCU values after 30 years of injection at 240 m³/hr. Impermeable Fault 2. The bulk of the values are in between 0.4 and 0.9, with 8% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 18% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 240 m³/hr, the probability of activation of impermeable Fault 2 by injecting 25°C water into the Delft formation via NLW-GT-04 is somewhat lower than the probability of activation of permeable Fault 2, but it is very similar to the probability of activation of impermeable Fault 2 but for 320 m³/hr. This suggests that acquiring more data in order to evaluate the permeability of

Fault 2 (e.g. carrying out a well test in NLW-GT-04) could be beneficial to possible design for higher injection / production rates in doublet 2.



5.3 Injector well NLW-GT-01 – injection into the Delft formation – Fault 3

Results of Fault 3 stability will be presented for one injection rate: 430 m³/hr @ 80% uptime (effectively 344 m³/hr). The lay-out is shown in Figure 5-43. Injection into well NLW-GT-01 (see top view) will result in a cold front moving around both sides of Fault 3. Therefore, the fault permeability will be irrelevant in this particular case. The south-east tip of Fault 3 is at a distance of ~ 800 m from NLW-GT-01. Once the cold front extends beyond the tip of Fault 3, the cross section along the dashed line in Fig. 5-43 schematically looks as shown in Fig. 5-43 as well. In this case, injection well NLW-GT-01 is 800 m out of the plane of the cross section.

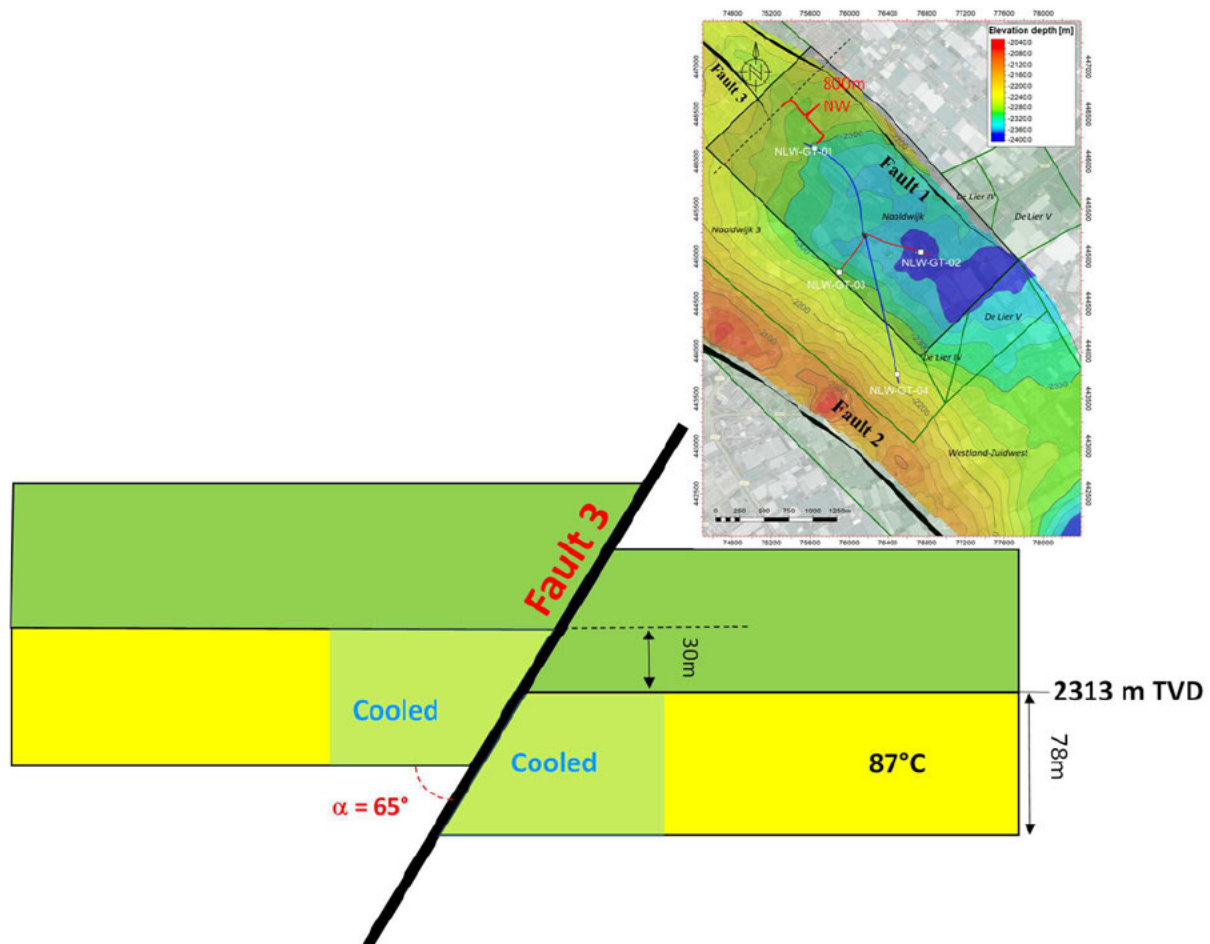


Figure 5-43 NLW-GT-01 Delft Fault 3: top view and side view (cross section) of injector and fault 3 along the dashed line indicated in the top view.

5.3.1 Temperature profile

The computed temperature profile away from the injector after 30 years of injection is presented in 5-44. The cooled zone is not an abrupt front but rather influenced by thermal diffusion, both within the reservoir and from the cap- and baserock into the reservoir.

After 30 years of injection we observe a temperature alteration up to ~900 m. This is considered the cold water “front”. The nearest tip of Fault 3 is expected at 800 m from NLW-GT-01. For a cold front with a radius of 900 m we can make a rough estimate of the extent of the “cooled” zones on either side of Fault 3 as indicated in the cross section of Fig. 5-43. Assuming a radially shaped cold front with a radius of 900 m and the fault tip at 800 m from injector NLW-GT-01, the extent of the cooled zone at the location of the fault tip is approximately equal to $\sqrt{900^2 - 800^2} \sim 410$ m on both sides of the fault. Using this cooled

zone of 410 m extent, the SCU along the fault is subsequently computed. As part of the uncertainty analysis, the distance between the fault tip and NLW-GT-01 is again varied ± 100 m, and corresponding extents of the cooled zone on either side of Fault 3 are used as input to SCU computations as well.

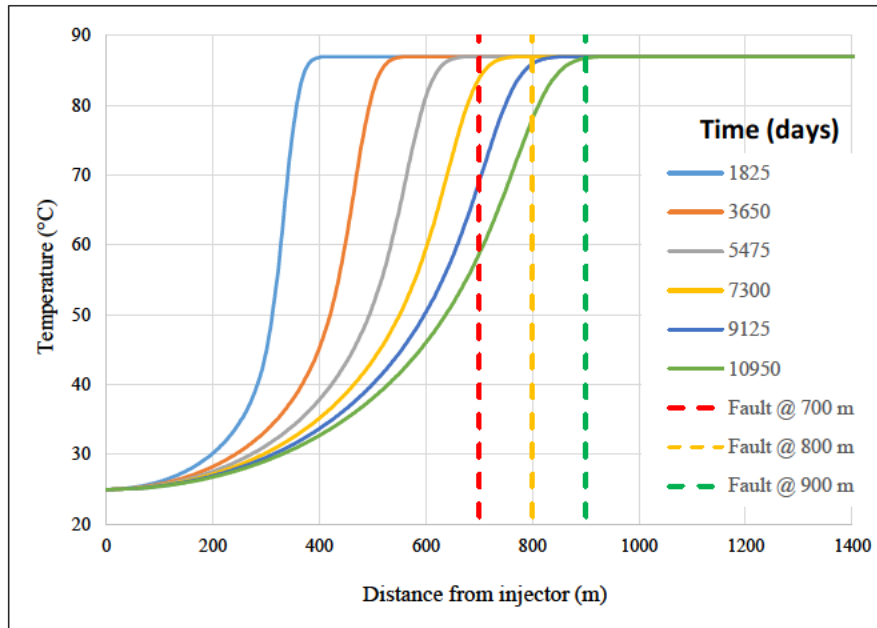


Figure 5-44 Temperature profile in the reservoir away from the injector after 30 years of injection of 344 m³/hr. In this figure, “Fault” means the tip of Fault 3 nearest to injector NLW-GT-01.

5.3.2 Deterministic analysis

The methodology as described in Section 3.1 is applied to estimate the impact of the cooling on the Shear Capacity Utilisation (SCU). In order to take into account the effect of partial cooling, the entire temperature profile in the cooled zones to the left and to the right of the fault is computed. Subsequently, the thermo-elastic stress change on the fault resulting from this temperature profile is calculated. As a fault position is a matter of interpretation and faults often display ‘damage zones’ an uncertainty was taken into account in the fault position of ± 100 m.

The results are given in Fig. 5-45, where the SCU is calculated for the initial state as well as the state of fault affected by a nearby cooled area. This shows the computed SCU along the fault after 30 years of injection at 344 m³/hr. It should be noted that, as in Fig. 5-43, the injection well is at a certain distance from the fault tip in a direction perpendicular to the plane of the figure. As can be seen, the maximum SCU for the base case (at vertical coordinate $x \approx -20$ m) is around 0.59 which is significantly below the limit for fault reactivation. Varying the distance between injector well NLW-GT-01 and fault tip over ± 100 m with respect to base case of 800 m results in an SCU-variation between 0.55 and 0.70. These SCU-values are significantly lower than obtained both for Fault 1 and Fault 2. The main reason for this difference is that Fault 3 is further away from NLW-GT-01 than Faults 1 and 2 are from NLW-GT-01 and NLW-GT-04, respectively.

Fig. 5-46 shows a deterministic failure analysis for the “worst” point on the SCU curve of Fig. 5-45. This figure shows the Mohr circles at the beginning of field life and after 30 years of injection at 344 m³/hr for Fault 3 at 800 m. The red dashed Mohr circle is obtained by assuming a uniform cooling down to the injection temperature of 25°C across the entire reservoir. The yellow dashed Mohr circle includes the actual change of state of stress as a result of the cooled area, i.e. it includes the impact of stress arching

by uncooled areas further away from the injector. Also, the approach presented here includes the impact of stress concentrations along the fault.

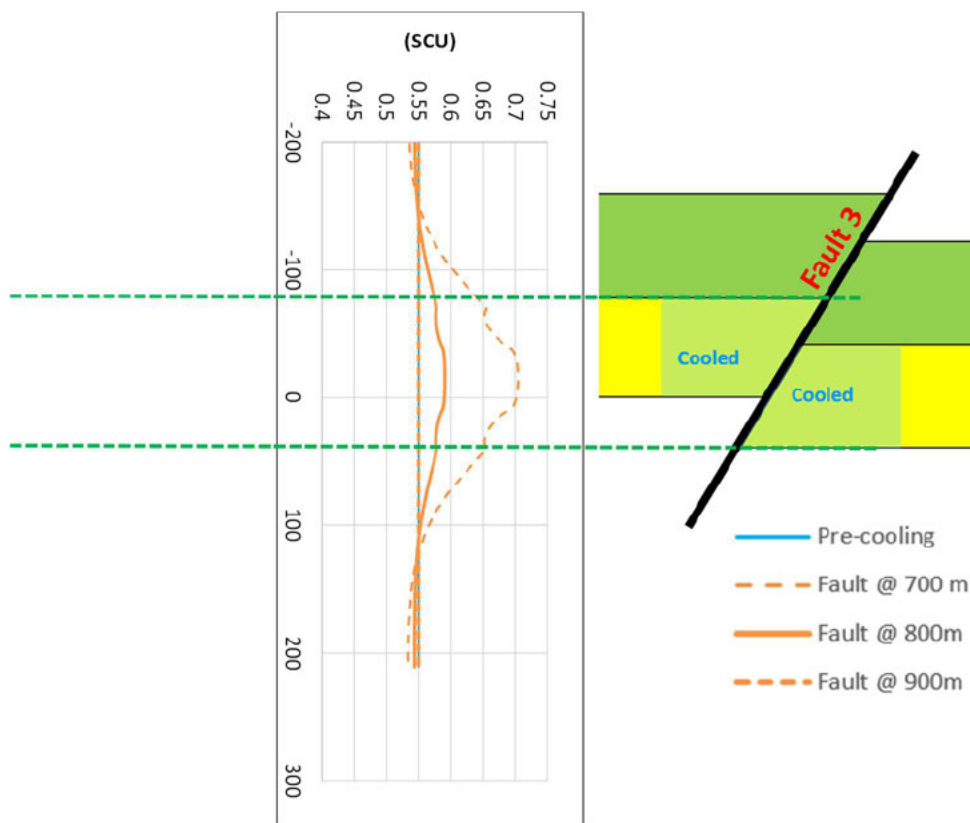


Figure 5-45 Computed SCU along the fault for injection rate 344 m³/hr and Fault 3. The “worst point” is addressed in a Monte-Carlo simulation. Dashed lines indicate the results based on a fault position uncertainty of ±100m.

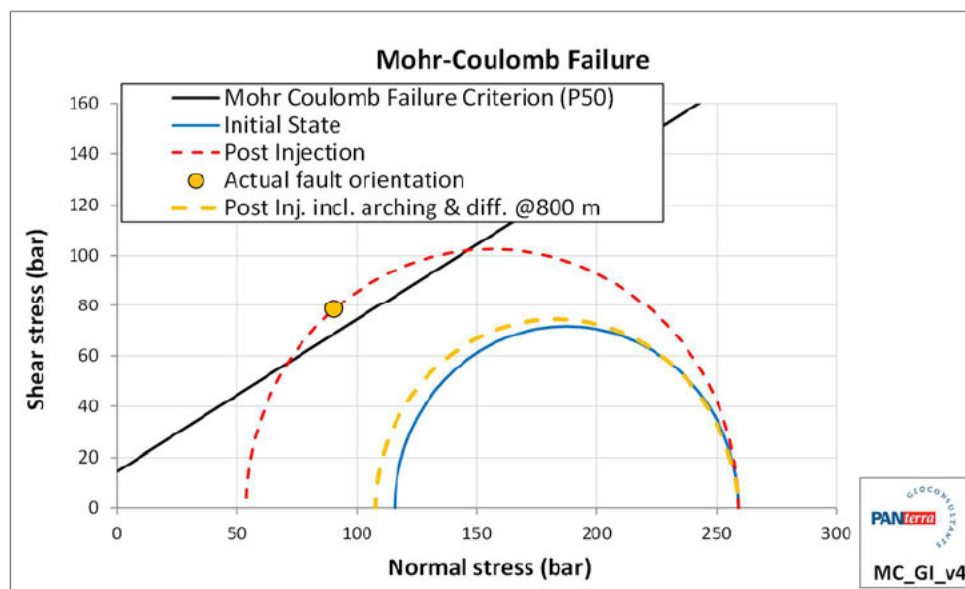


Figure 5-46 Mohr circles for injection rate 344 m³/hr and Fault 3 at the “worst” point along the fault (see fig. 5-45).

It should be noted that the impact of stress arching is very pronounced in this case (Fig. 5-46). This can be explained by the fact that in the current case (Fault 3) the lateral extent of the cooled zone (see Fig. 5-45) is fairly limited (410 m). Moreover, in this case the cooled zone extent is limited on both sides of the fault, contrary to the other cases where the cooled zone extent is large on the injector side of the fault.

5.3.3 Probabilistic analysis (Monte Carlo)

In order to address the impact of parameter uncertainties, a Mohr-Coulomb Monte-Carlo analysis was carried out using an ensemble of 1000 members. The addressed uncertain parameters are shown in Table 5-1, which displays the input parameters for the probabilistic analysis of the Delft formation and Fault 3, including their low-med-high values. The parameters and reasoning have been discussed in section 4.3.

Table 5-3 Input parameters for probabilistic analysis of the Delft formation and Fault 3. See text for discussion.

	Parameter	Min	Median	Max
Rock Parameters	Reservoir Temperature (°C)	84	87	90
	Thermoelastic coefficient (bar/°C)	0.5	1.0	1.5
	Vertical stress gradient (bar/m)	0.21	0.22	0.23
	Horizontal stress gradient (bar/m)	0.144	0.158	0.189
Fault Parameters	Cohesion (bar)	0	15	30
	Friction coefficient (-)	0.48	0.60	0.72
	Dip (degrees)	55	65	75
	Distance from injector (m)	700	800	900

The results of this analysis are shown in Fig. 5-47 and Fig. 5-48. The majority of SCU values seen are in the 0.4-0.9 range, with 6% having an SCU between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 10% an SCU > 1 (based on the P90 Mohr-Coulomb failure line).

In conclusion, after 30 years of injection at 344 m³/hr, the probability of activation of Fault 3 by injecting 25°C water into the Delft formation via NLW-GT-01 could be considered “low”.

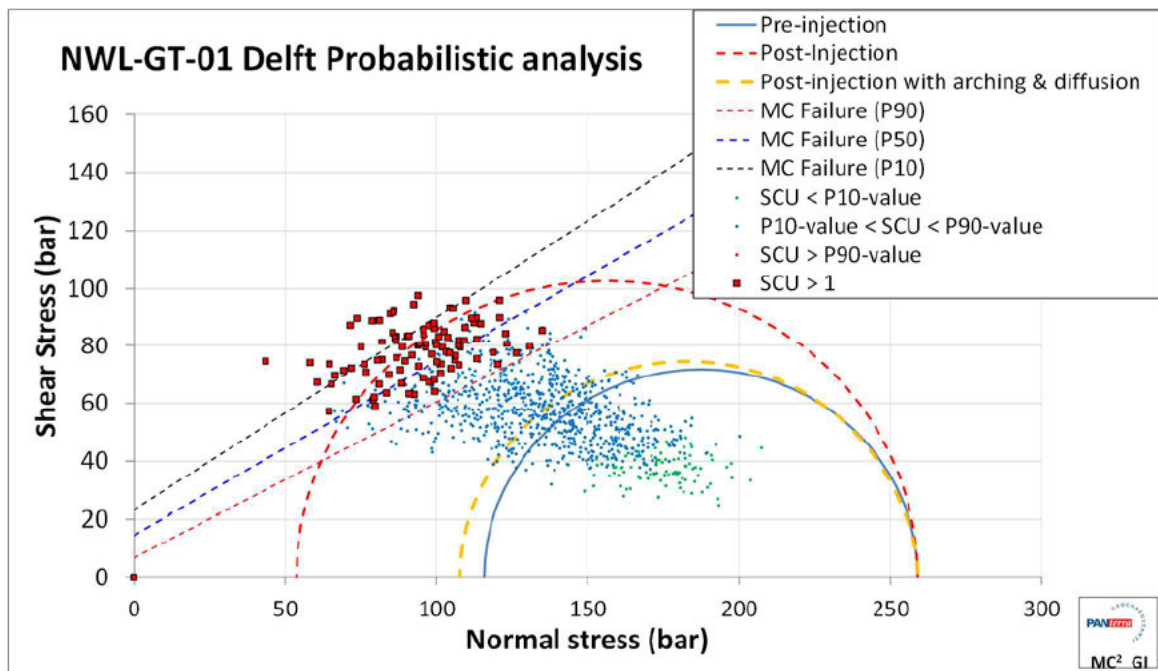


Figure 5-47 Results of Mohr-Coulomb Monte-Carlo for cooling around Fault 3 as a result of injection into injector NLW-GT-01, after 30 years of injection at 344 m³/hr. The dots represent the simulations, colours indicating the P10,P50 and P90 results. Three reference Mohr Circles are presented based on the median input: initial state (blue solid circle), result assuming full reservoir cooling (red-dashed circle) and result including arching & temperature diffusion (orange-dashed circle).

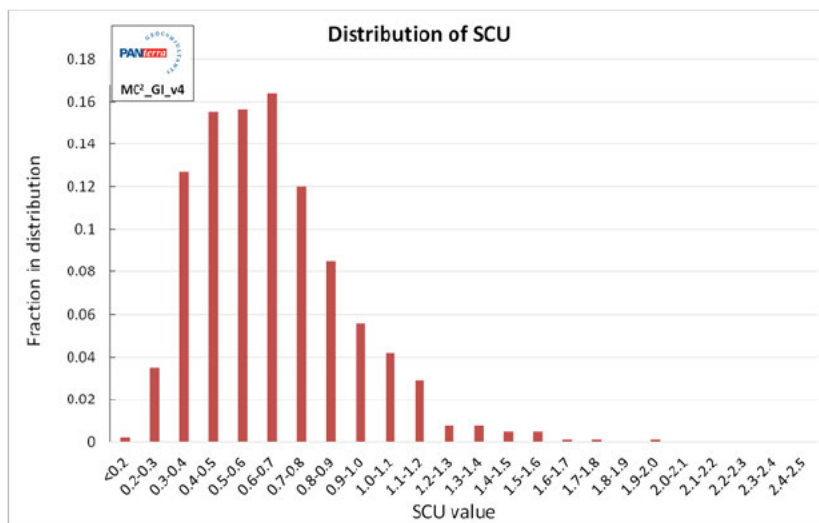


Figure 5-48. Probability diagram of the simulated SCU values after 30 years of injection at 344 m³/hr. Fault 3. The bulk of the values are in between 0.4 and 0.9, with 6% between 0.9 and 1 (based on the P90 Mohr-Coulomb failure line), and 10% with SCU > 1.0 (based on the P90 Mohr-Coulomb failure line).

6 Conclusions

This report presents a level-2 SHA study for Trias-Westland. The results can be summarised as follows:

Fault 1 and NLW-GT-01

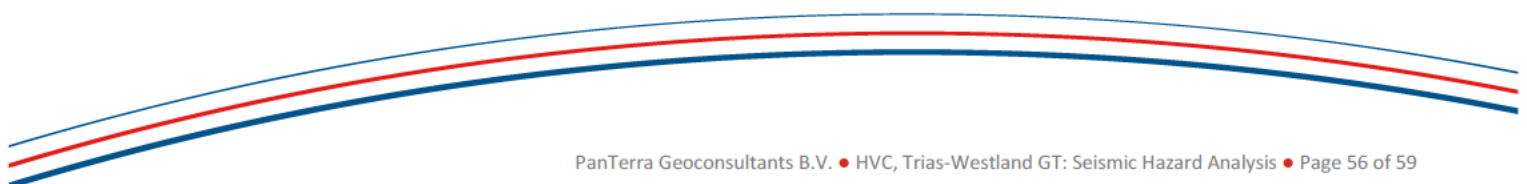
- For $t = 30$ yrs @ 344 m³/h (430 m³/h @ 80% uptime), the risk of fault reactivation is non-negligible (20% of SCU > 1) as a result of the fact that the cold front has crossed the fault and cools part of the reservoir at the opposite side.
- This applies both for a conservative approach (permeable fault, 20% of SCU > 1) and a non-conservative approach (sealing fault, 14% of SCU > 1).
- For $t = 30$ yrs @ 240 m³/h (300 m³/h @ 80% uptime), the risk of fault reactivation is lower (10% of SCU > 1). This applies both to a permeable and an impermeable fault. This is because after 30 yrs of injection, the cold front just about “touches” the fault.

Fault 2 and NLW-GT-04

- For $t = 30$ yrs @ 320 m³/h (400 m³/h @ 80% uptime) and the conservative assumption of a permeable fault, the risk of fault reactivation is non-negligible (44% of SCU > 1) as a result of the fact that the cold front has crossed the fault and cools part of the reservoir at the opposite side.
- For a permeable fault, the risk of fault reactivation is higher in GT-04 than in GT-01 because the cold front in GT-04 has crossed further into the opposite side of the fault (injector closer to fault, lower thickness of Delft sandstone).
- For the assumption of a sealing fault, the risk of fault reactivation (20% of SCU > 1) is comparable to that of GT-01 (14% of SCU > 1).
- For $t = 30$ yrs @ 240 m³/h (300 m³/h @ 80% uptime), the risk of fault reactivation is lower (29% of SCU > 1 for a permeable fault, 18% of SCU > 1 for an impermeable fault).
- This is more than GT-01 with reduced injection rate because of the closer proximity to the fault and lower thickness of the Delft formation.

Fault 3 and NLW-GT-01

- For $t = 30$ yrs @ 320 m³/h (400 m³/h @ 80% uptime), the risk of fault reactivation is significantly lower (10% of SCU > 1) than the other two cases.
- Please note, that because Fault 3 is parallel to the line between injector NLW-GT-01 and the tip of fault 3, both sides of (part of) this fault will be flooded, independent of its (fault) permeability.



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