Haagsche Aardwarmte Leyweg (HAL)
Seismic Hazard Analysis

Date: January 2020

Prepared by: [redacted] & [redacted]

Reviewed by: [redacted]

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Summary

1. Geological setting warranted a **(level-2)** Seismic Hazard Analysis
2. Mohr Coulomb and Finite Element models show the faults in HAL r**emain stable**
3. Under Groningen depletion conditions, faults in HAL would **remain stable**
4. There is a **very low** possibility that an unmapped fault reaches a critical state under **worst case** fault and production parameters
5. Extreme scenario would have a maximum possible magnitude in the order of Mw = 1.6 **after 30 years**
   - This is considered very unlikely (<0.1% chance)
   - A TLS is set up to mitigate the potential impact. Possible other mitigation measures are decrease of injection pressure and increase the injection temperature.

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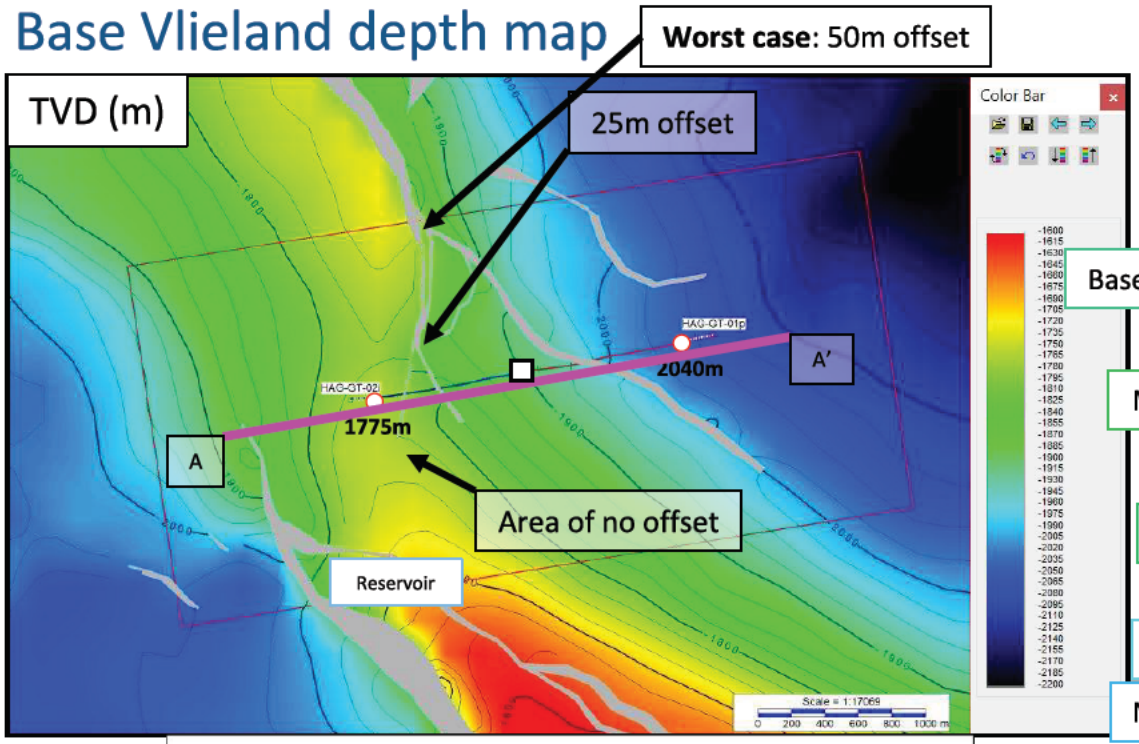
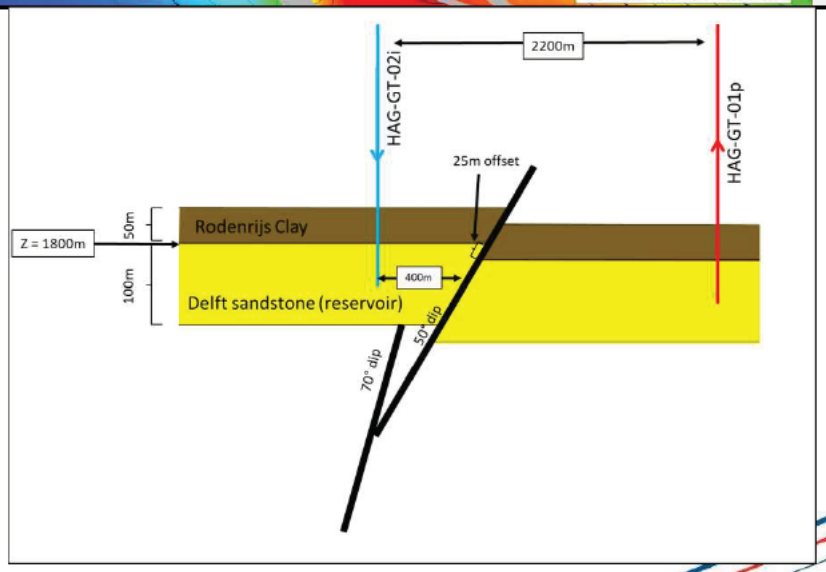
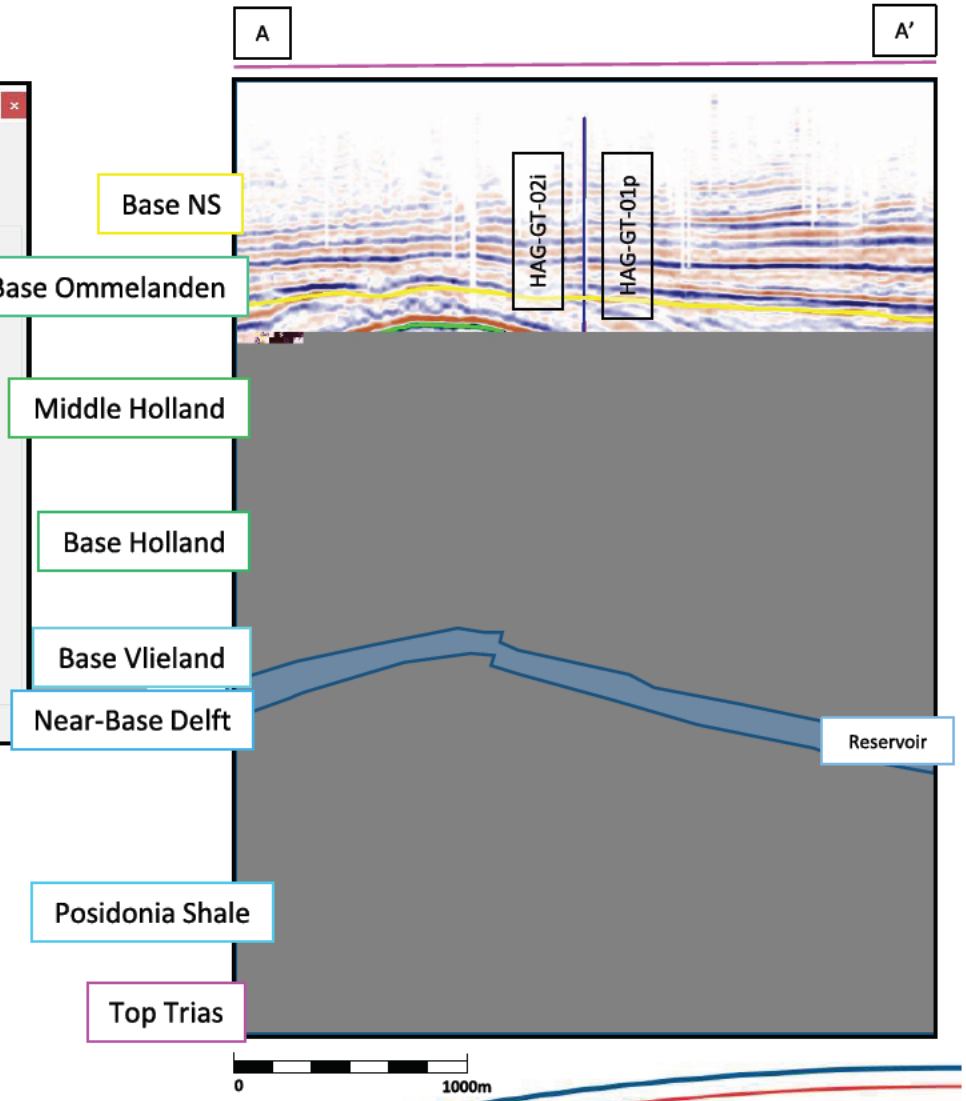
Geological Setting HAL

Base Vlieland depth map







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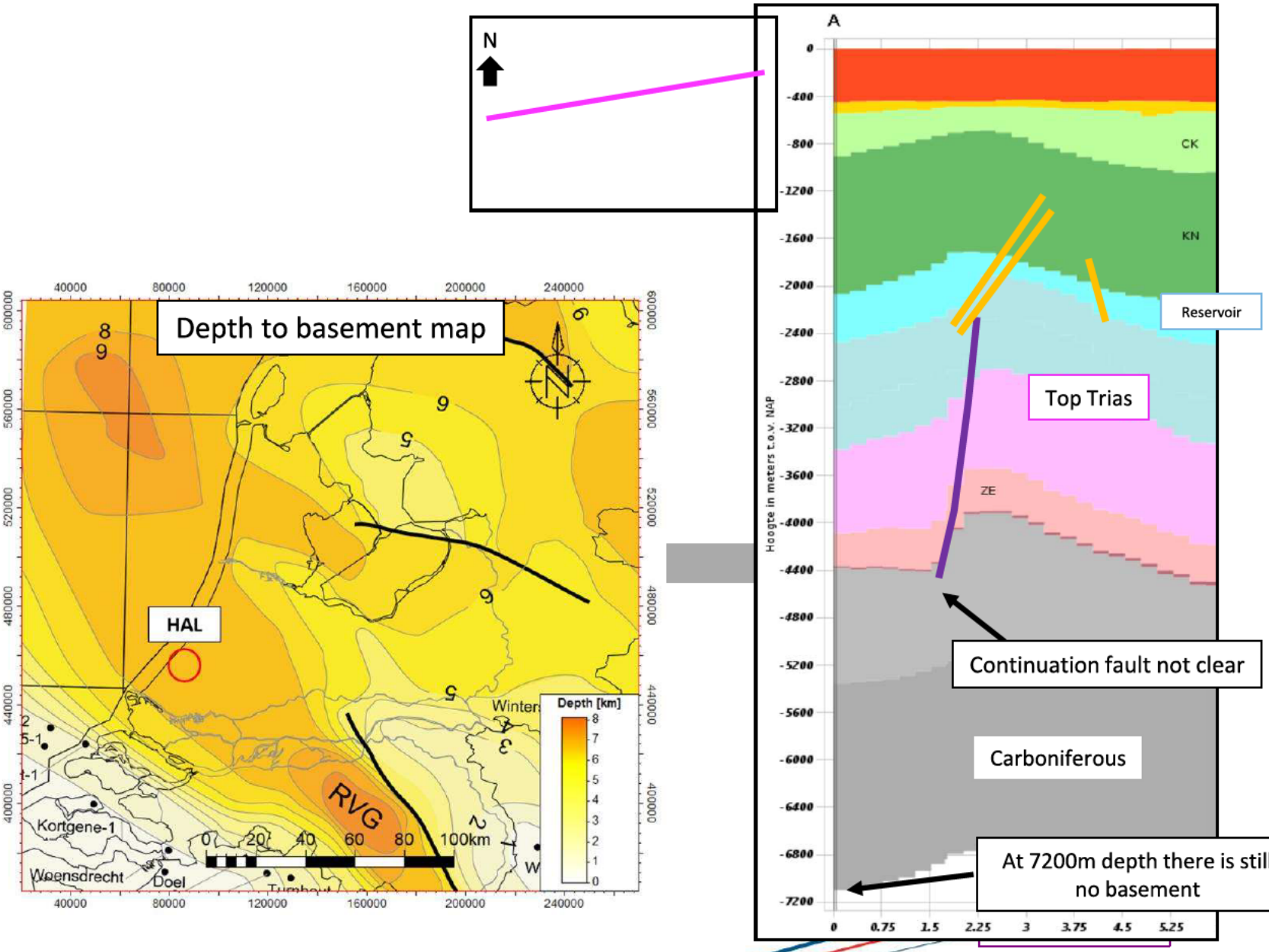
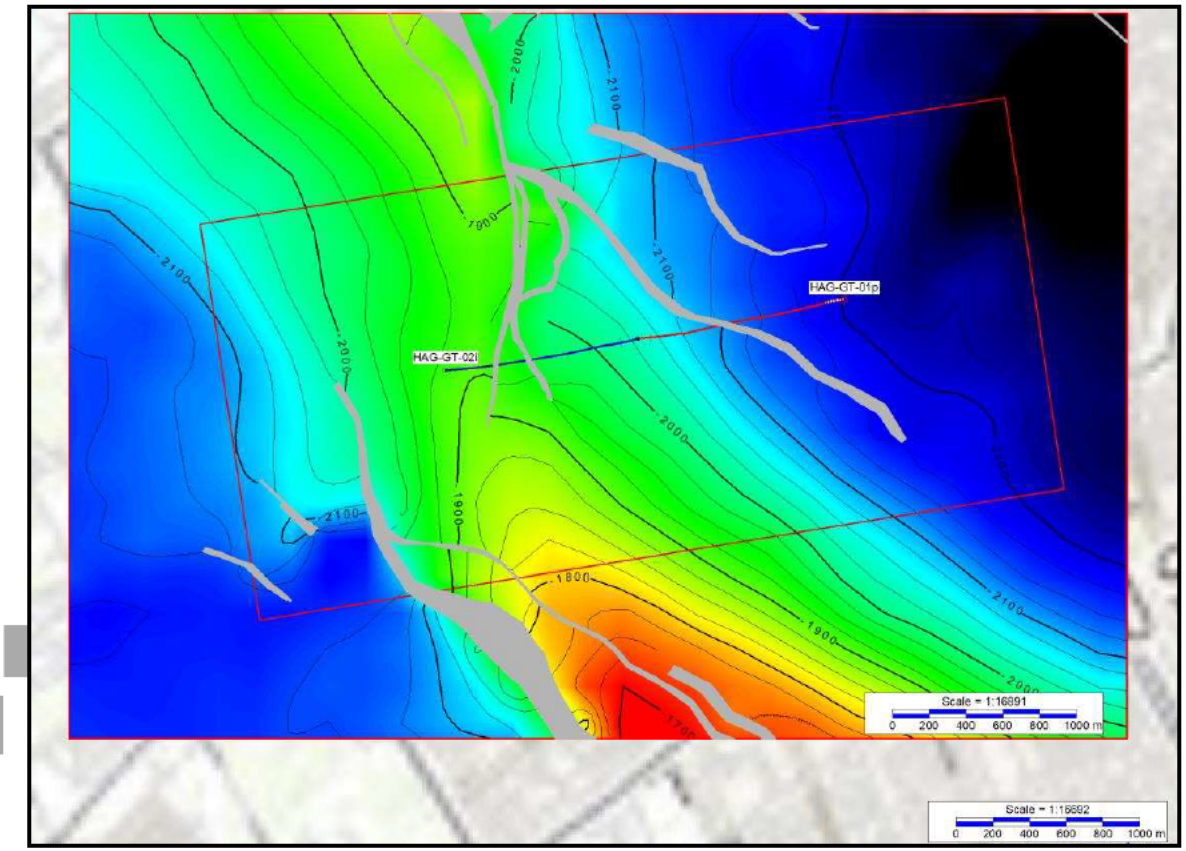
Continuation in depth



Connectivity HAL

- HAG-GT-02i well test: 1400 mD
- HAG-GT-01p well test: 2300 mD
- Interference test: Minimum of 280 mD
- Less high permeability of interference test is most likely caused by a lower fault permeability and/or offset along the fault reducing connectivity



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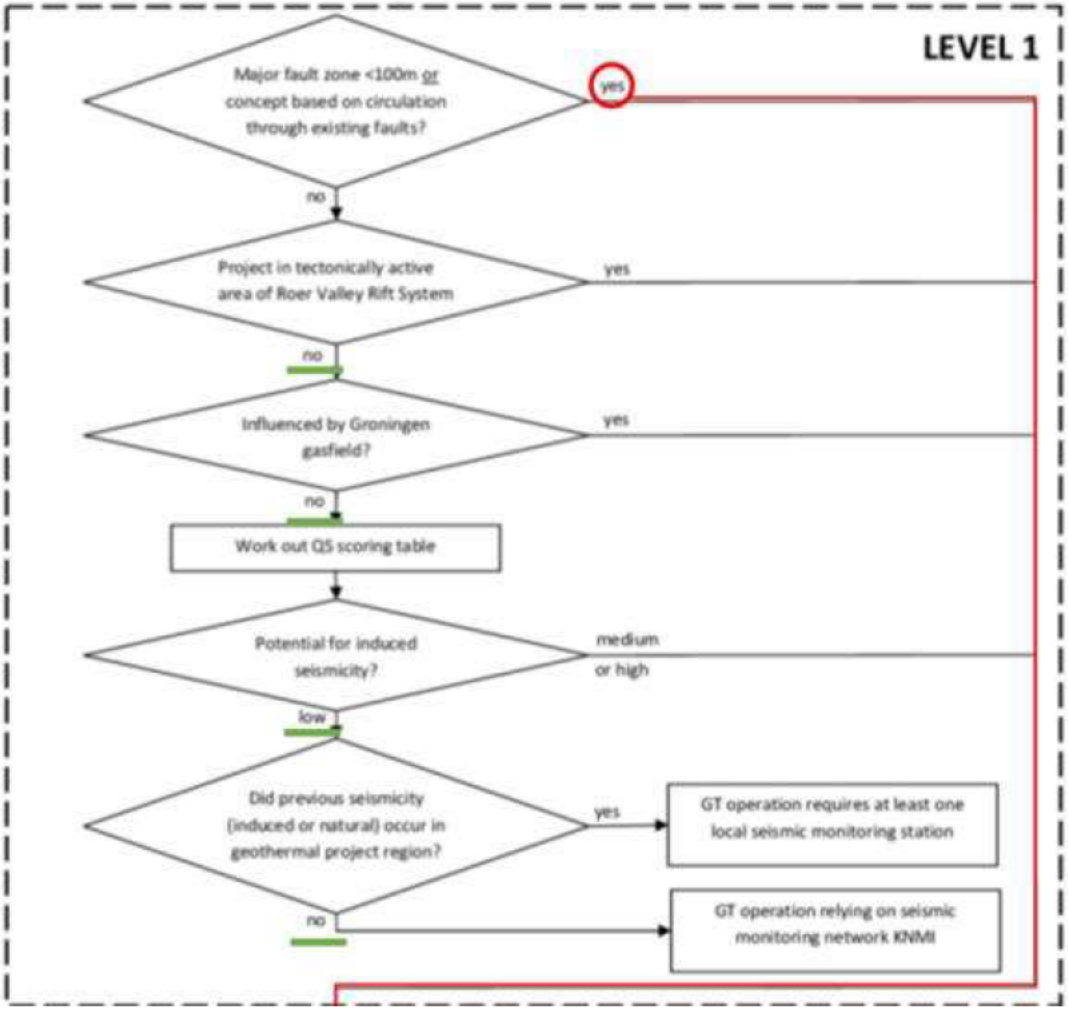
SHA for geothermal systems

- SHA based on *QCON/IF, Defining the Framework for Seismic Hazard Assessment in Geothermal Projects, October 2016*
- Result of SHA Level 1 QuickScan: low seismic risk **(score = 0.26)**
- Due to
  - Offset in the reservoir
  - Proximity to faults and fault zone
  - Planned production through a fault

    → a SHA Level 2 will be executed.



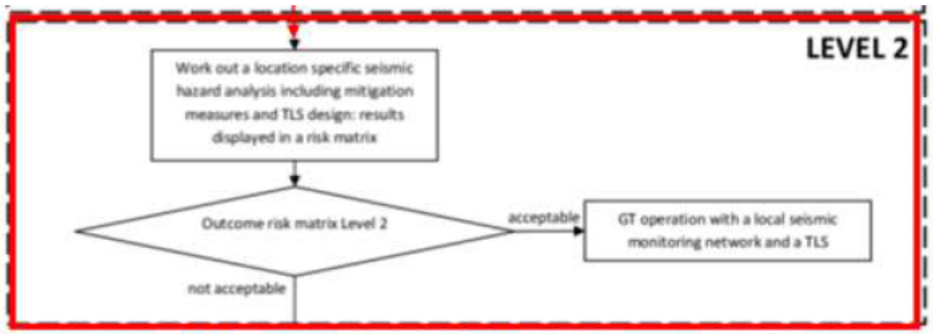


Figure 5-1. Level 1 SHA assessment for HAL based on the IF/QCON guidelines.

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SHA Level 1: QuickScan HAL

Table 2-1 SHA scoring scheme for TWL-2. The applicable scores are highlighted in red. From the individual scores a normalised QS score of 0.26 is calculated.

Score	Basement connected	Inter-well pressure communication	Re-injection pressure [MPa]	Flow rate [m³/h]	Epicentral distance to natural earth quakes [km]	Epicentral distance to induced seismicity [km]	Distance to fault [km]	Orientation of fault in current stress field	Net injected volume [1000 m³]
10	Yes	No	>7	>360	<1	<1	<0.1	Favourable	>20
7	Possible	Unlikely	4-7	180-360	1-5	1-5	0.1-0.5	Shearing possible	5-20
3	Unlikely	Likely	1-4	50-180	5-10	5-10	0.5-1.5	Shearing unlikely	0.1-5
0	No	Yes	<1	<50	>10	>10	>1.5	locked	<0.1

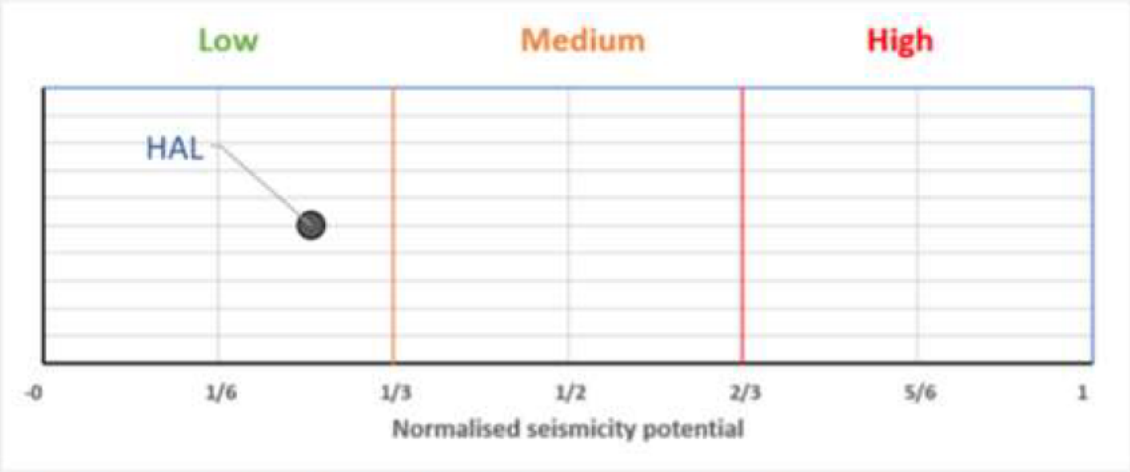

Figure 5-2. Result of the SHA QS-Scoring table as put forward by IF/QCON.

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Mohr Coulomb Stress Field: HAL

- Density logs show a vertical stress gradient for HAL of **σ_1 = 0.214 bar/m**
- Leak Off Tests and Formation Integrity tests show the minimum horizontal stress gradient at **σ_3 = 0.165 bar/m**
- Groningen relations between **σ_3** and **σ_2** show a maximum horizontal stress of **σ_2 = 0.184 bar/m**
- The EBN Geo-drilling events database (GDE) was advised but contained no better constraints on the stress situation near HAL
- *For details see Appendix 1*

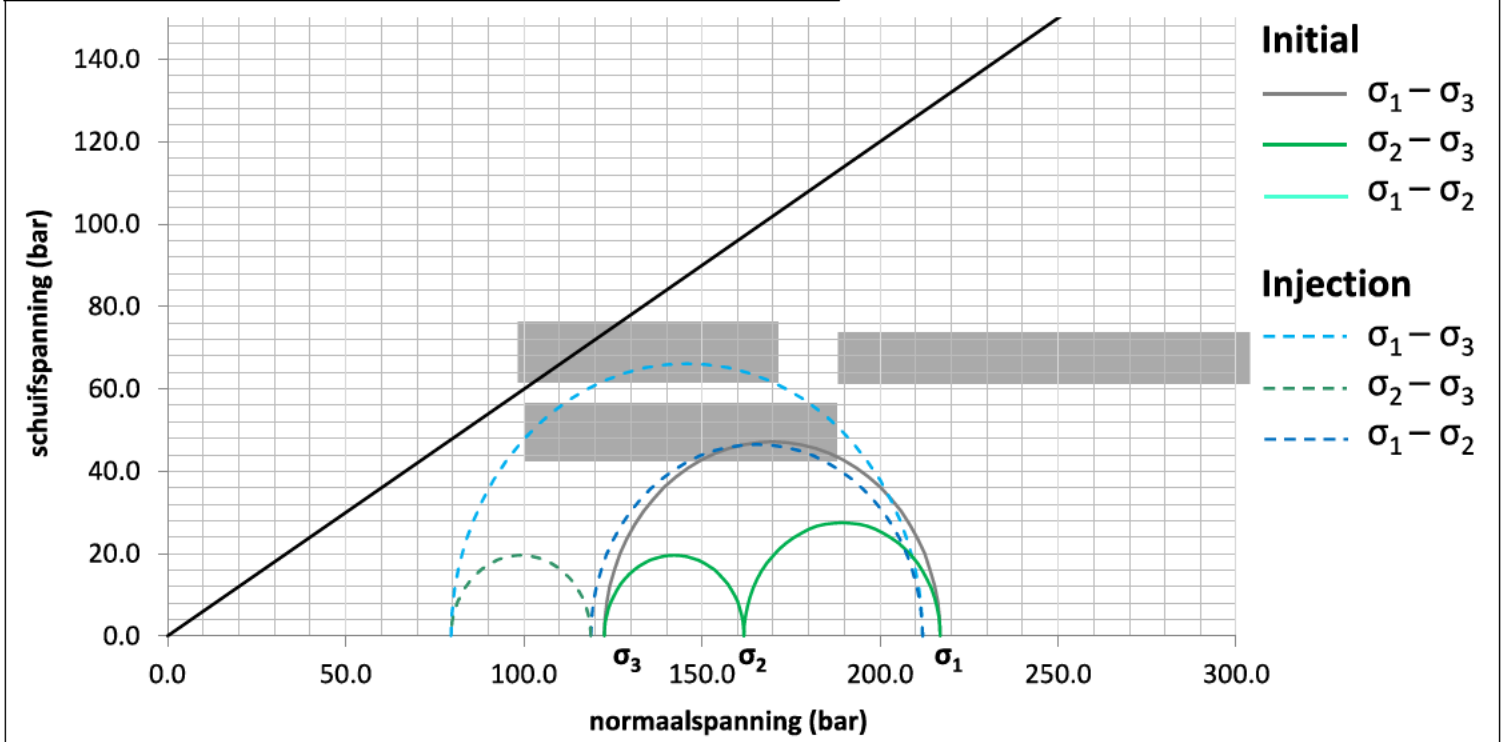
Mohr Coulomb model: HAL

- Situation after injection is closer to the failure line

Under these already conservative parameters no failure is expected

Injection Temperature: **45°C**
ΔP at injector: 5 bar (**150m³/hr** injection rate)

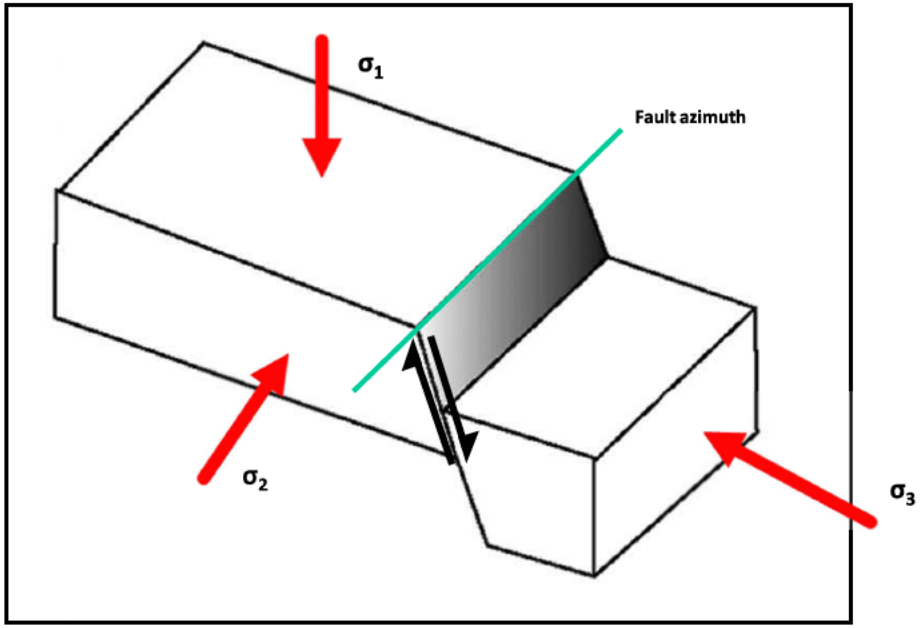
3-D Mohr-Coulomb failure diagram HAL

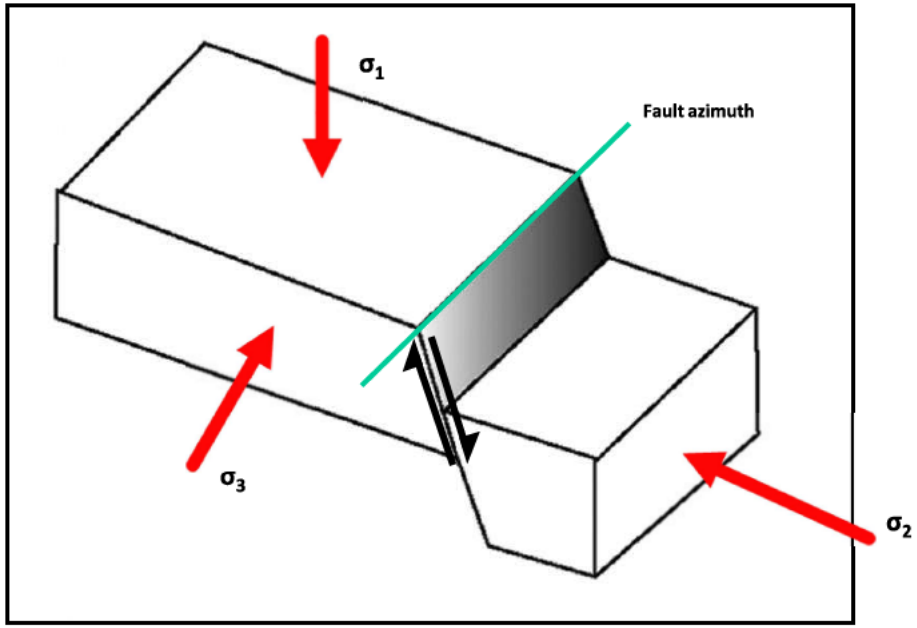


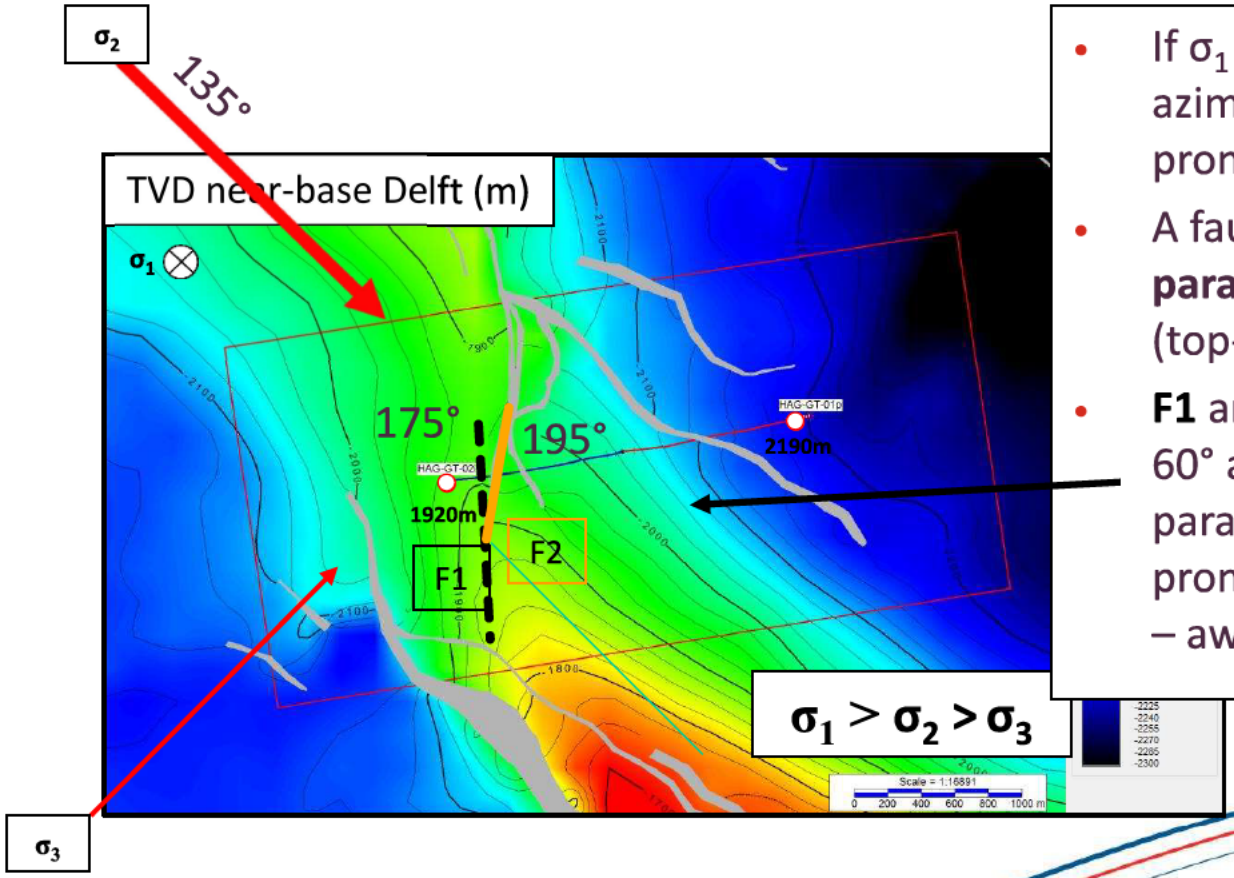
- Young's Modulus E = 10 GPa
- Poisson's ratio v = 0.3
- Thermal expansion coefficient $\alpha = 1 \cdot 10^{-5}$
- Frictioncoefficient μ = 0.6
- $T_{reservoir}$ = 73°C
- Re-injection temperature = 45°C (Winter scenario)
- **No cohesion assumed**

For interpretation see Appendix 2

Production parameters: worst case (winter)
Fault parameters: worst case
Reservoir parameters: conservative







- If $\sigma_1 > \sigma_2 > \sigma_3$, and $\boldsymbol{\sigma_2}$ is **parallel** to the fault azimuth, the fault is more 'open' and more prone to failure (top-left figure)
- A fault with an azimuth perpendicular to σ_2, or **parallel** to $\boldsymbol{\sigma_3}$, is in the most stable orientation (top-right figure)
- **F1** and **F2** are orientated at an angle of 40° and 60° and therefore more stable than fault parallel to σ_2. This is reflected in a position less prone to failure in the Mohr-Coulomb analysis – away from the 'large' circle (next slide)

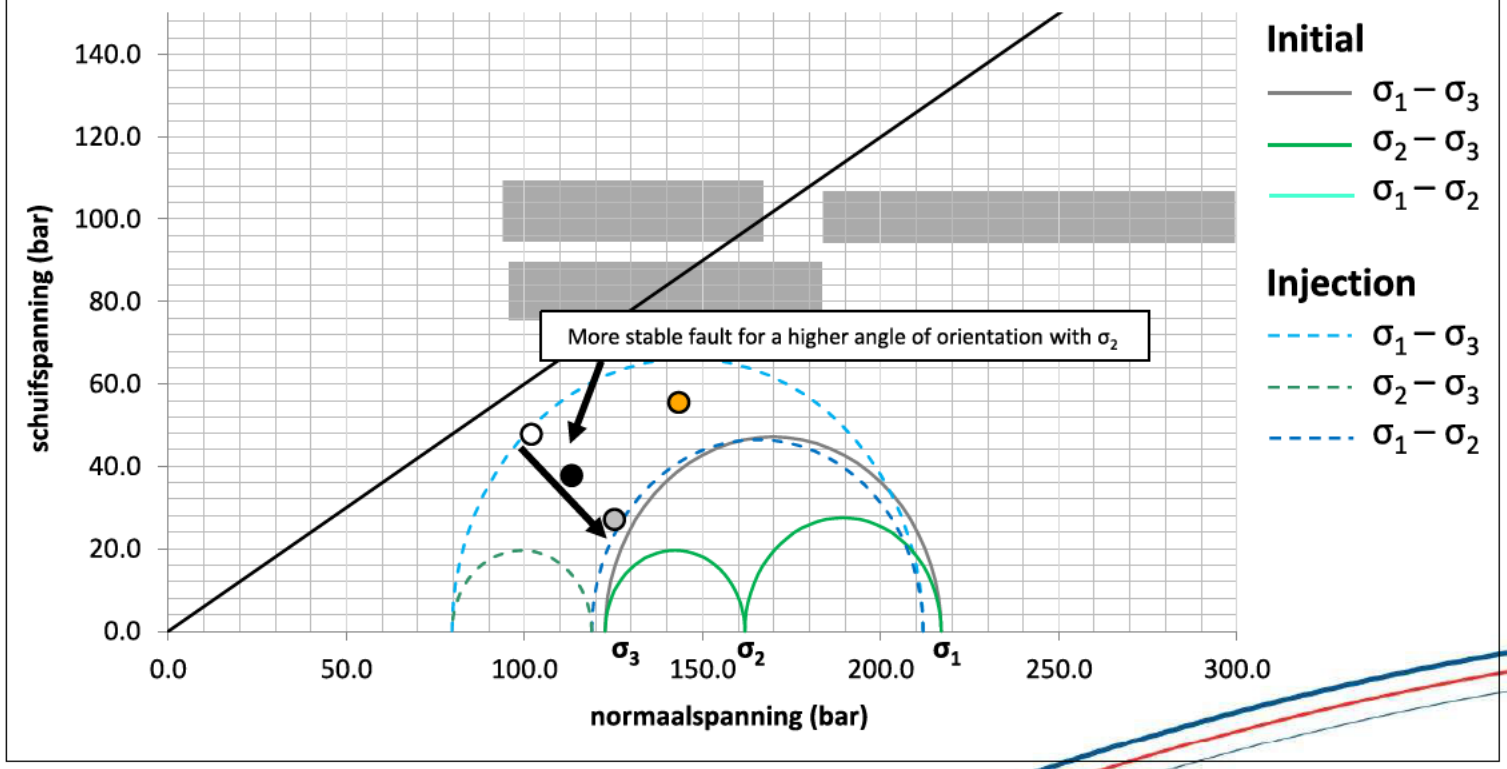
Mohr Coulomb analysis: impact of fault azimuth

- Fault situation in HAL is more stable than a situation where faults are parallel to the maximum horizontal stress σ_2
- This is already for a conservative production scenario

Production parameters: worst case (winter)
Fault parameters: expected
Reservoir parameters: conservative

Injection Temperature: **45°C**
ΔP at injector: 5 bar (**150m³/hr** injection rate)

3-D Mohr-Coulomb failure diagram HAL



Fault azimuth perpendicular on σ_3

Fault azimuth perpendicular on σ_2

F1 HAL

F2 HAL

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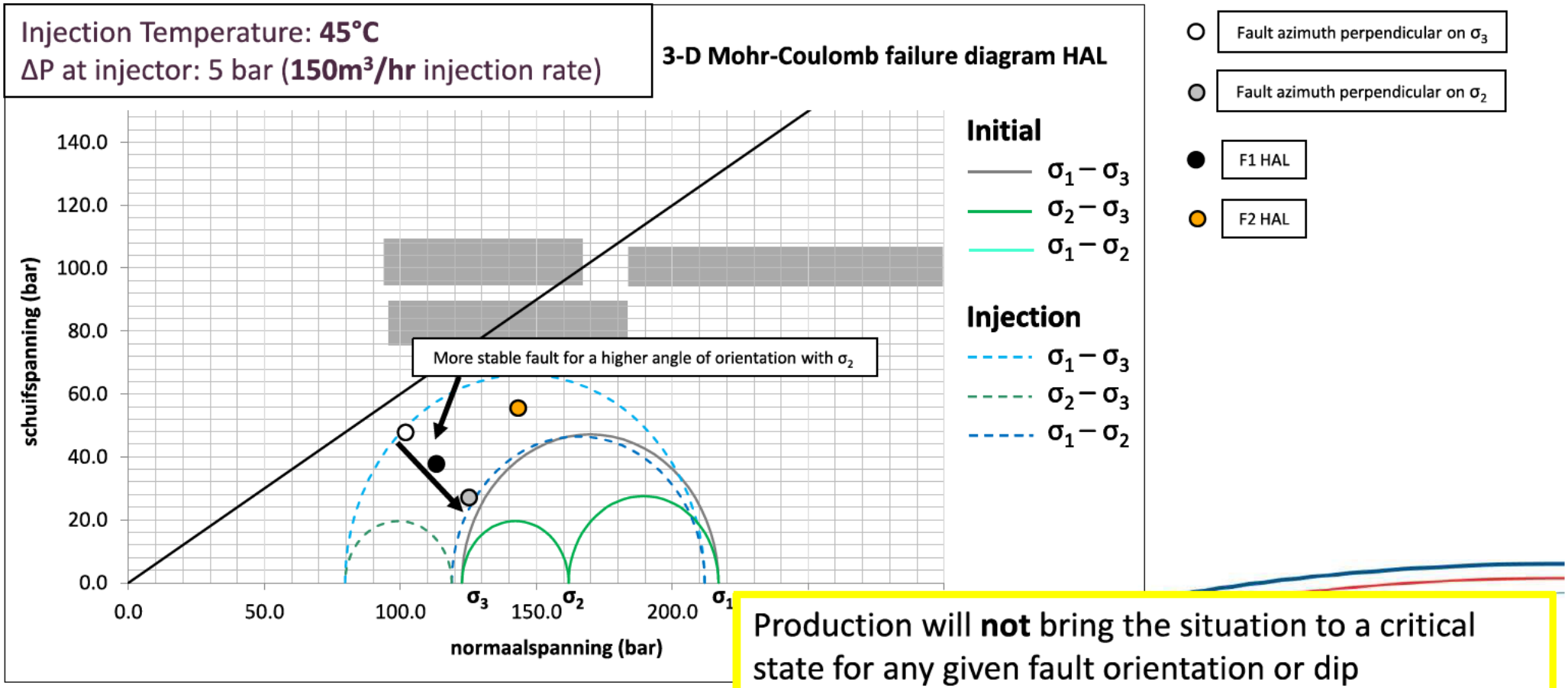
Mohr Coulomb analysis

- Fault situation in HAL is more stable than a situation where faults are parallel to the maximum horizontal stress σ_2
- This is already for a conservative production scenario

Production parameters: worst case (winter)
Fault parameters: expected
Reservoir parameters: conservative

Injection Temperature: **45°C**
ΔP at injector: 5 bar (**150m³/hr** injection rate)



Production will **not** bring the situation to a critical state for any given fault orientation or dip
The mapped faults are even less prone to failure

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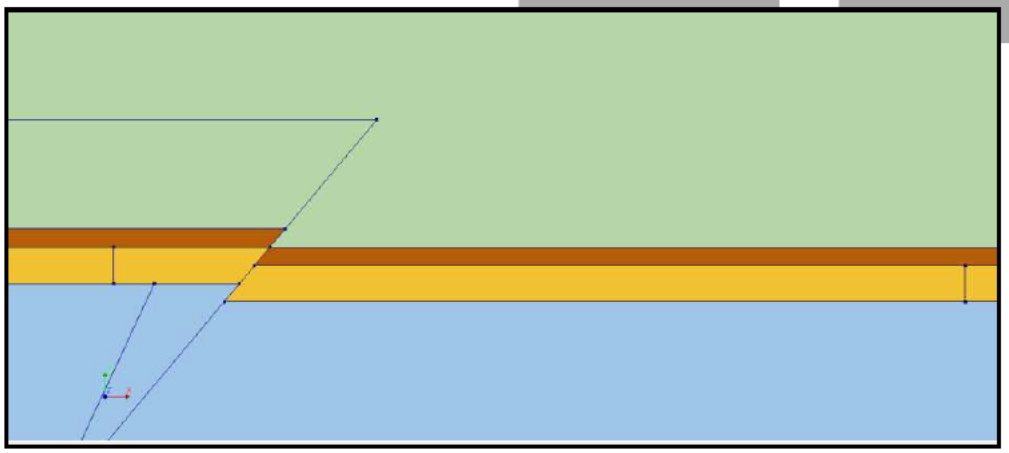
Finite Element Analysis(1)

- Mohr-Coulomb only looks at one point in the subsurface
- Does not take into account:
  - Geometrical effects
  - Effects of local stress concentrations
  - Effect of stress arching
  - Etc.
- In order to capture the above, build 2D finite element model and simulate lifecycle for one doublet
  - Fully coupled: fluid flow – thermal convection / diffusion- stress calculations – failure & slip calculations
- In building FE model, follow a similar approach as published for Groningen depletion *(Buijze, v.d. Bogert et al)*

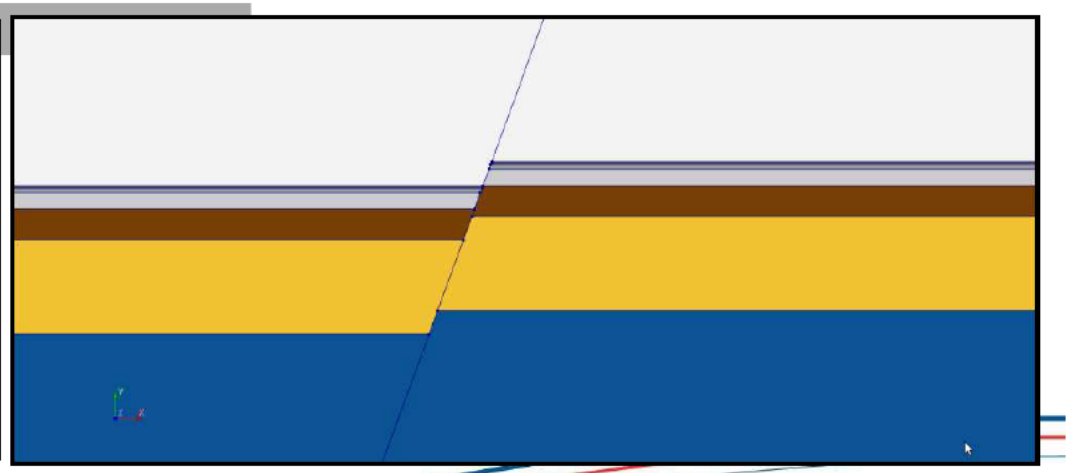
Finite Element Analysis(2)

- 'Calibration' against Groningen:
  - Build same Groningen FE model as Buijze et al
  - Use this to compute fault slip as a function of depletion
  - Estimate maximum seismic magnitude based on the above
  - Build & run similar FE model for HAL case, & compute fault slip
  - Analyze & explain differences Groningen ↔ HAL

HAL



Groningen



Finite Element: Groningen case calibration

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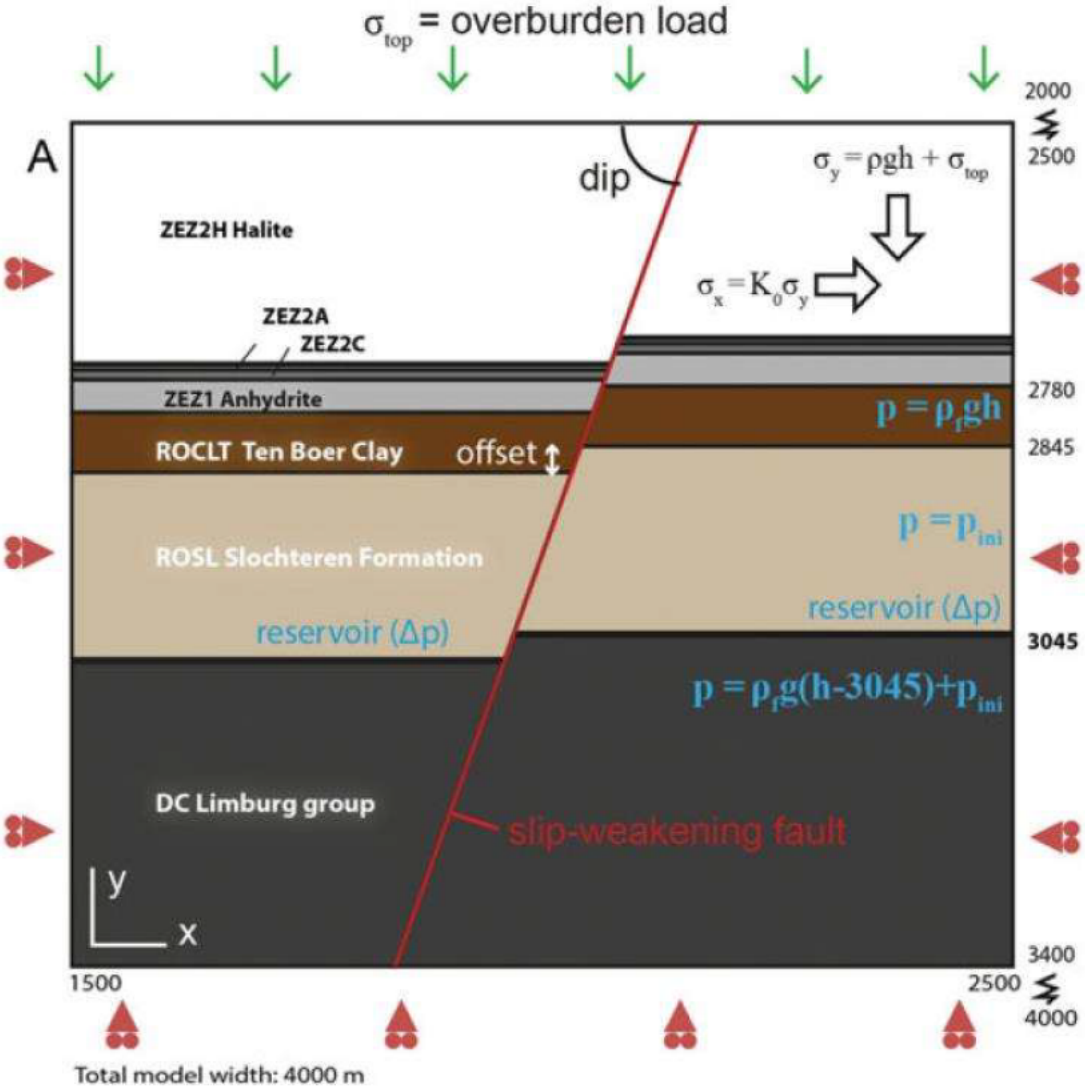
Groningen Depletion



"Fault reactivation mechanisms and dynamic rupture modelling of depletion-induced seismic events in a Rotliegend gas reservoir"

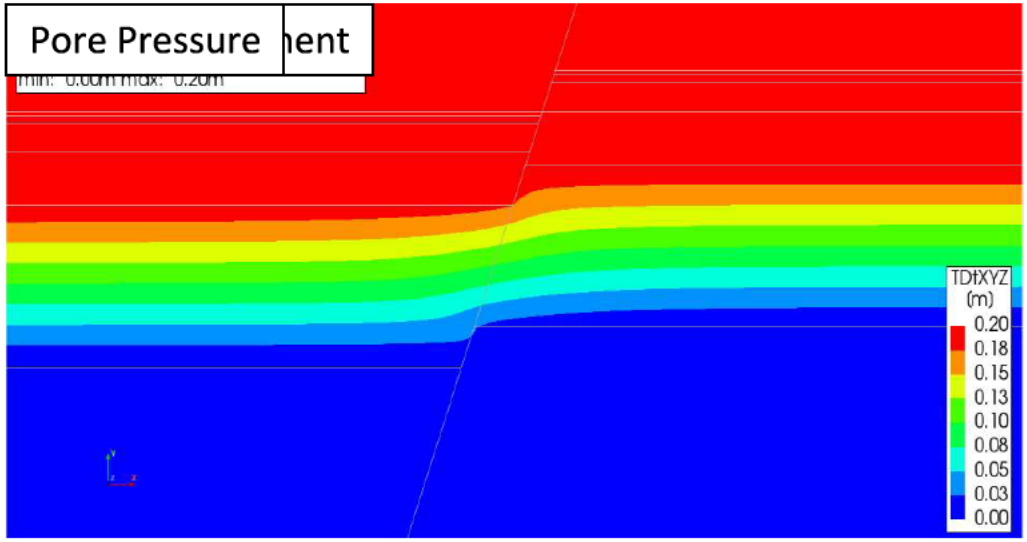
- Buijze et al., 2017

Groningen Depletion

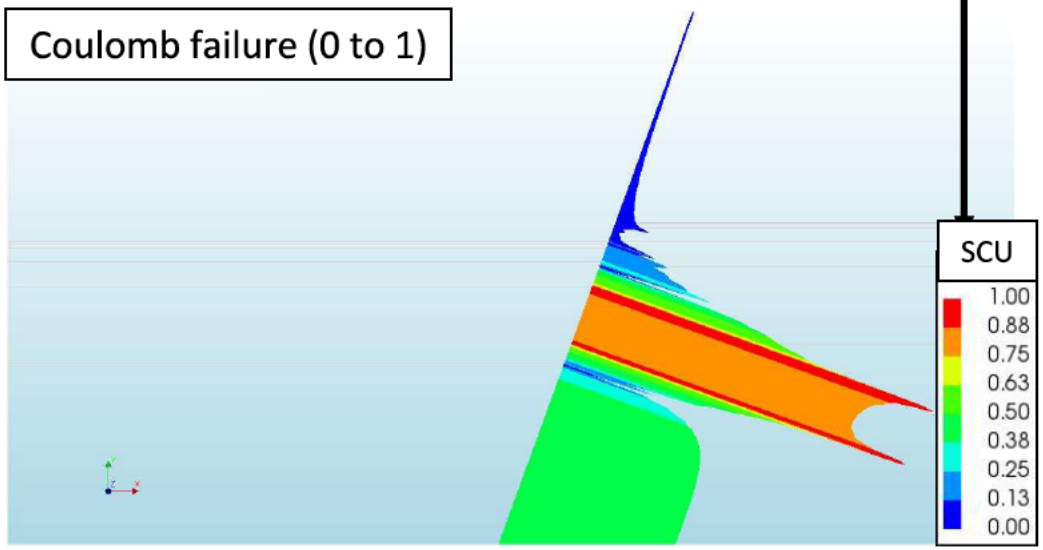
DEPLETION: 155 BAR (± 1987)

Distance to coulomb failure.
A value of **1** is coulomb failure.
Below this we have elastic behaviour

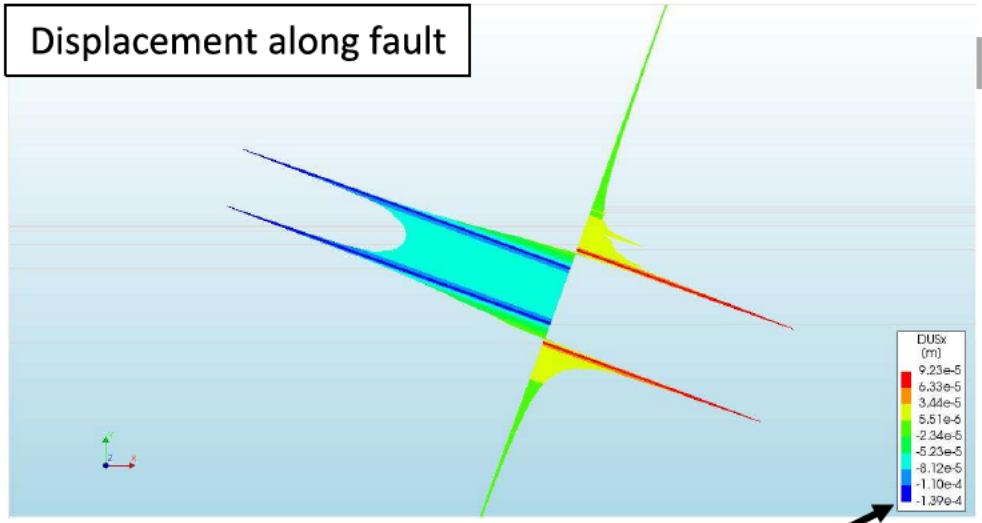
Pore Pressure ent



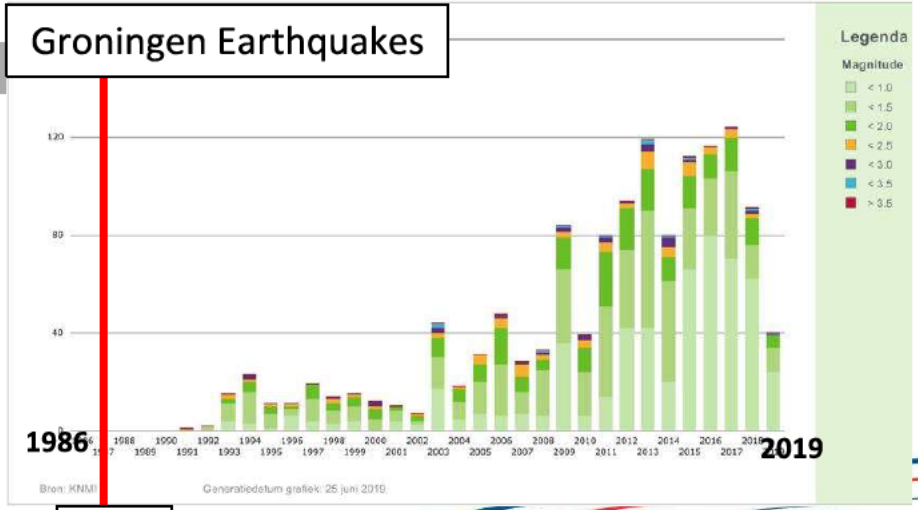
Coulomb failure (0 to 1)



Displacement along fault



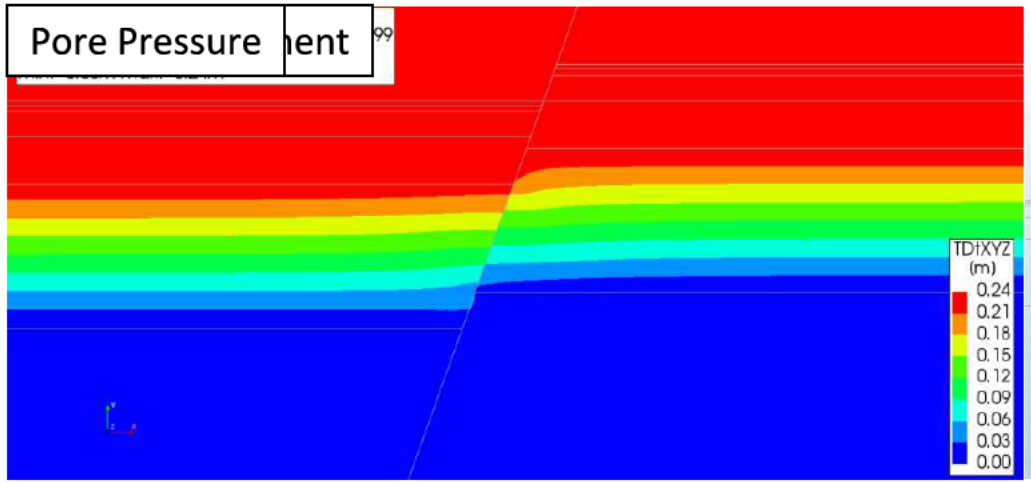
Groningen Earthquakes

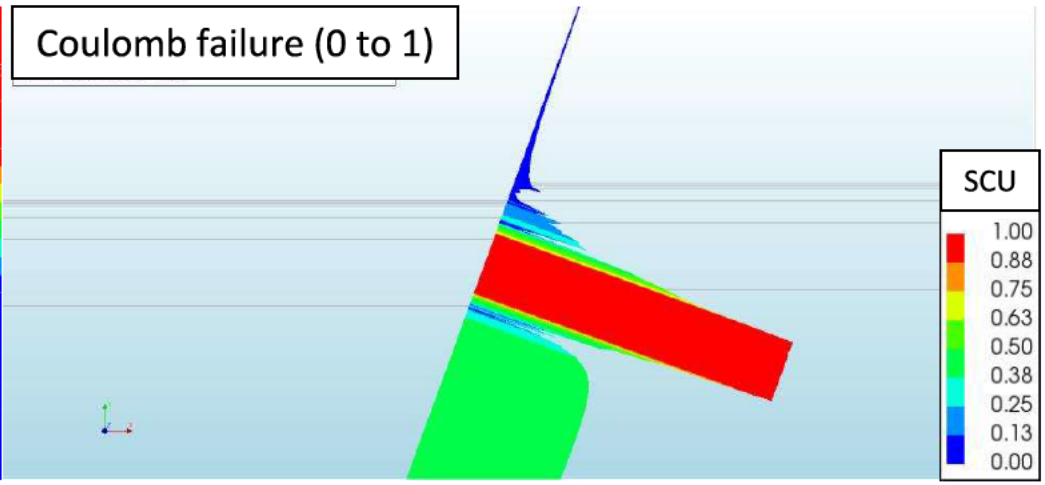


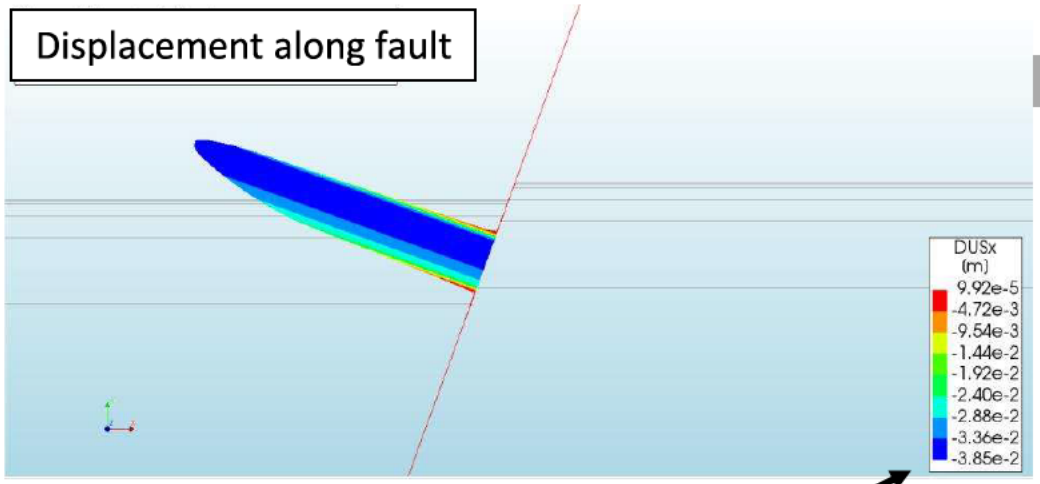
1/10th milimeter

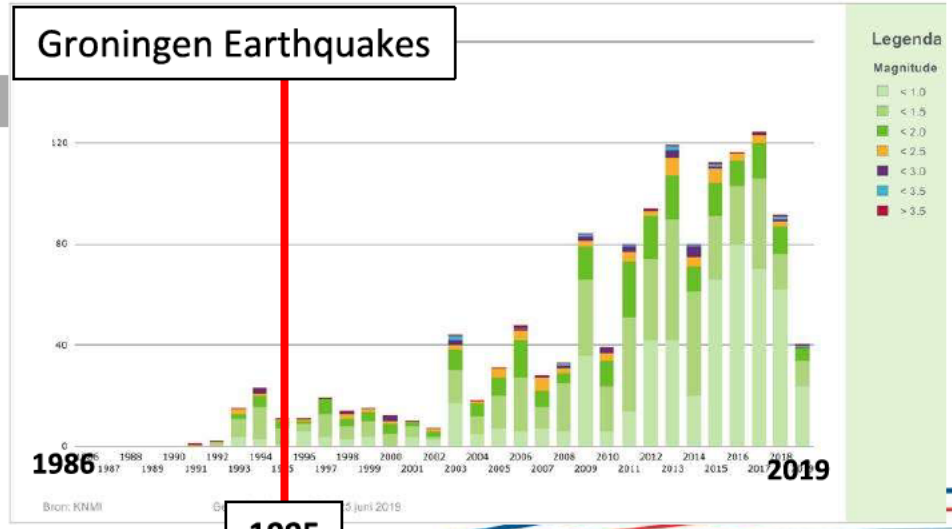
Groningen Depletion

DEPLETION: 180 BAR (± 1995)





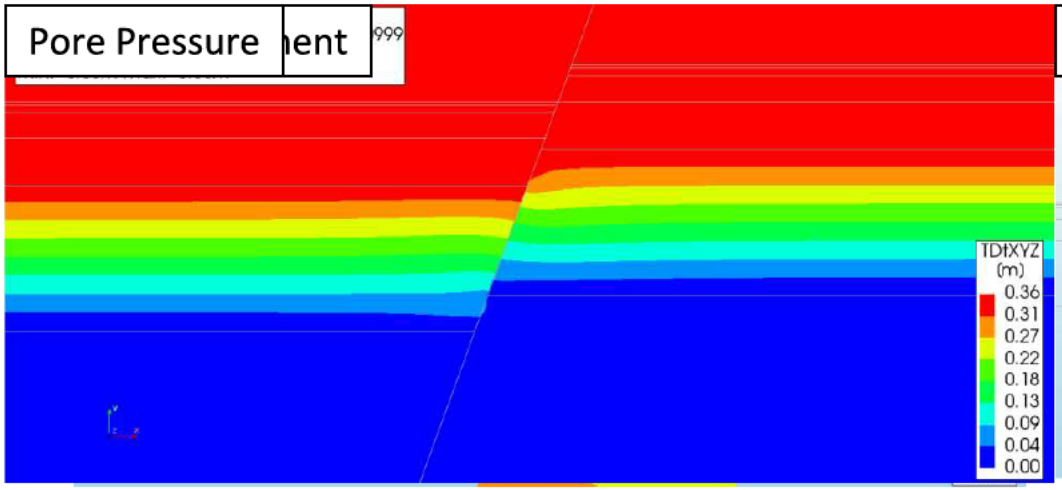


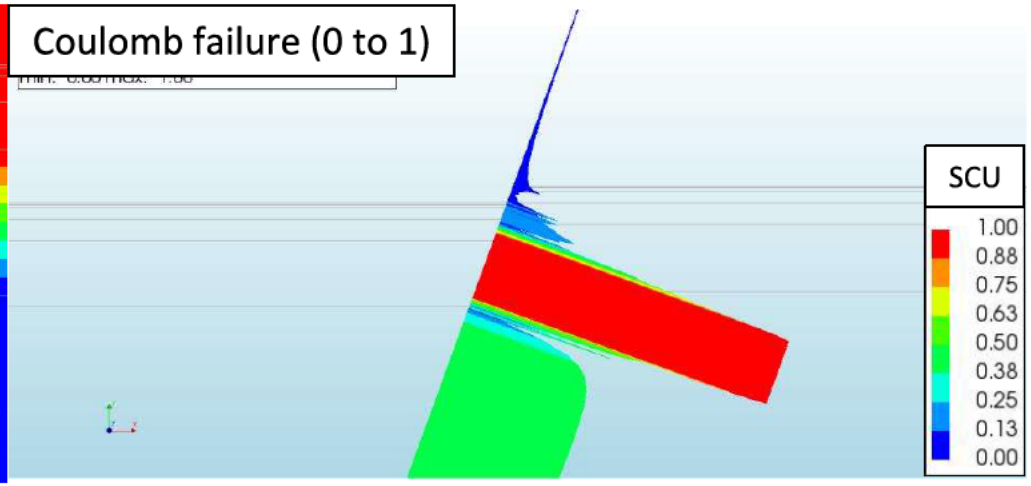


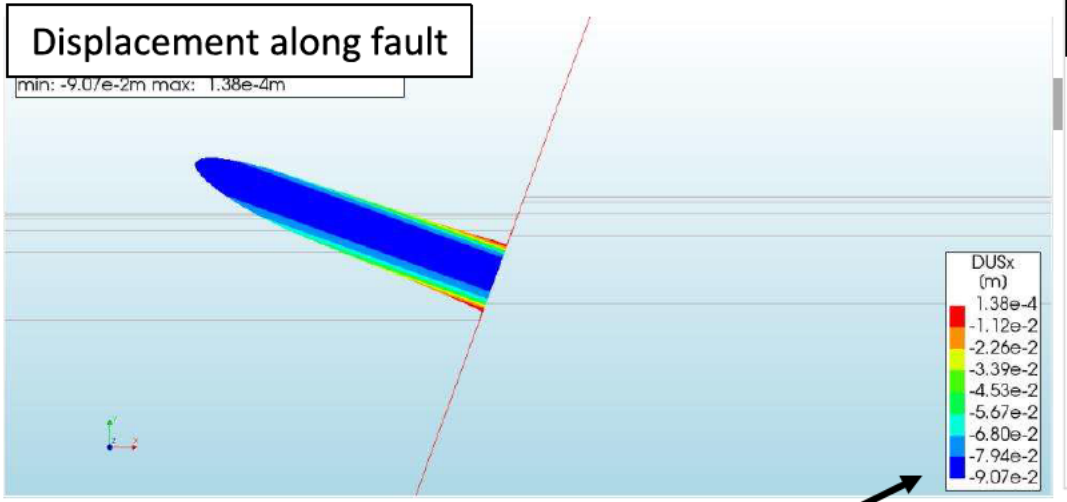
~3 Centimeter

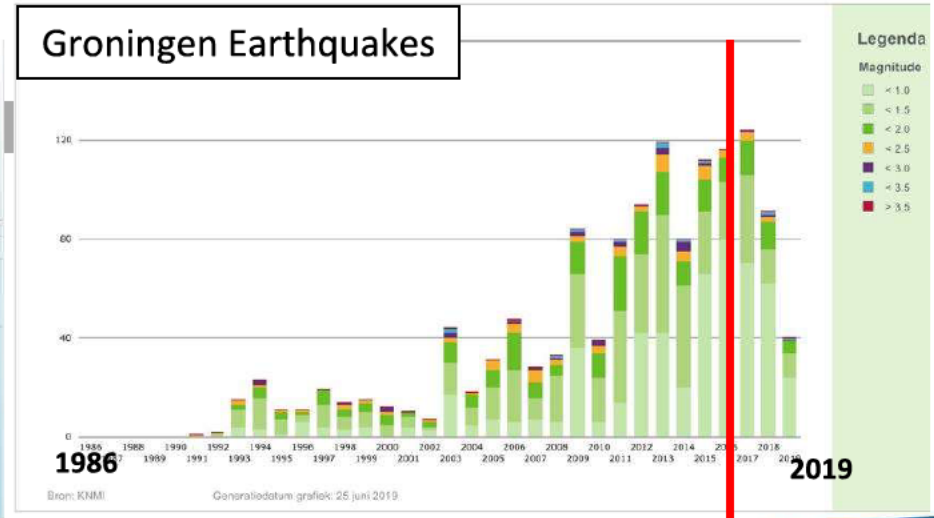
Groningen Depletion

DEPLETION: 270 BAR (± 2016)



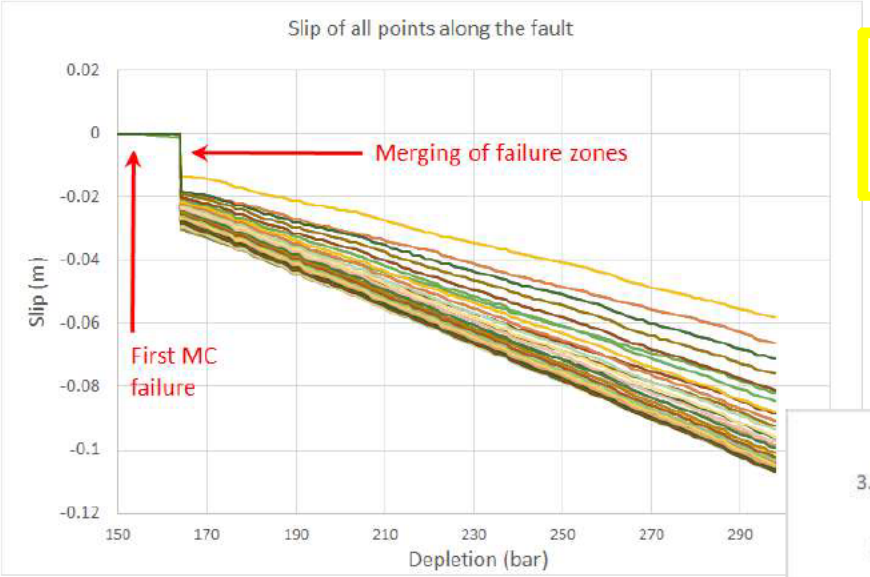




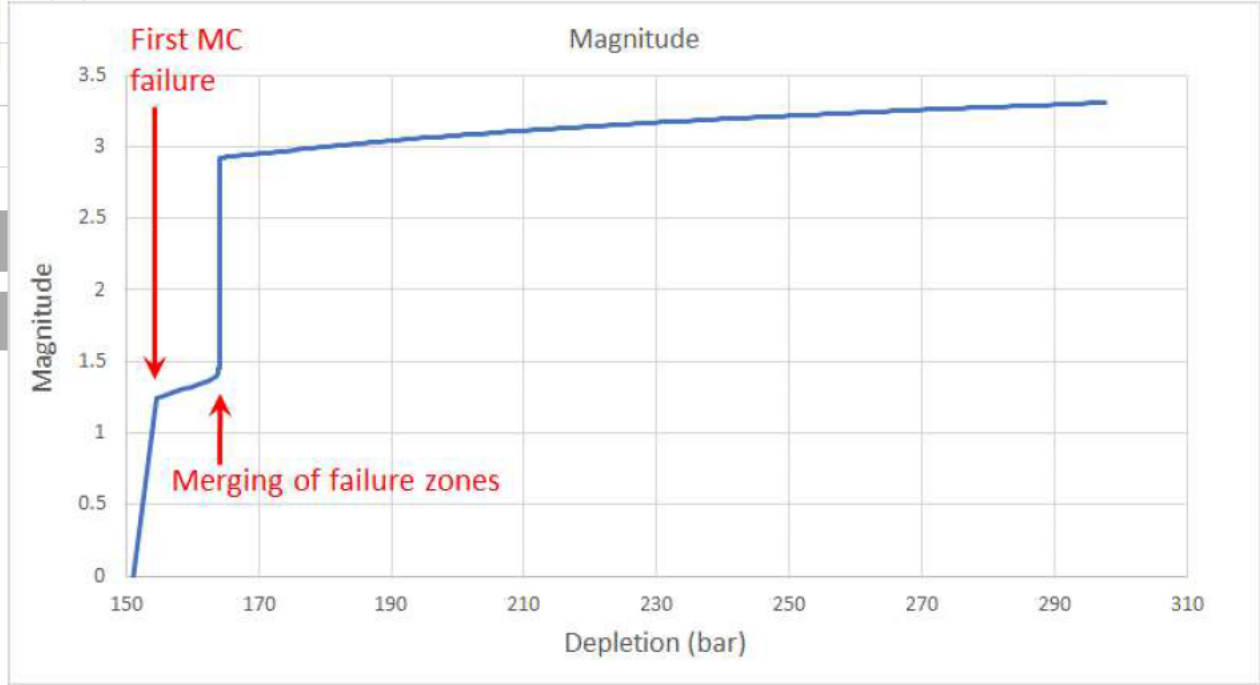


~9 Centimeter

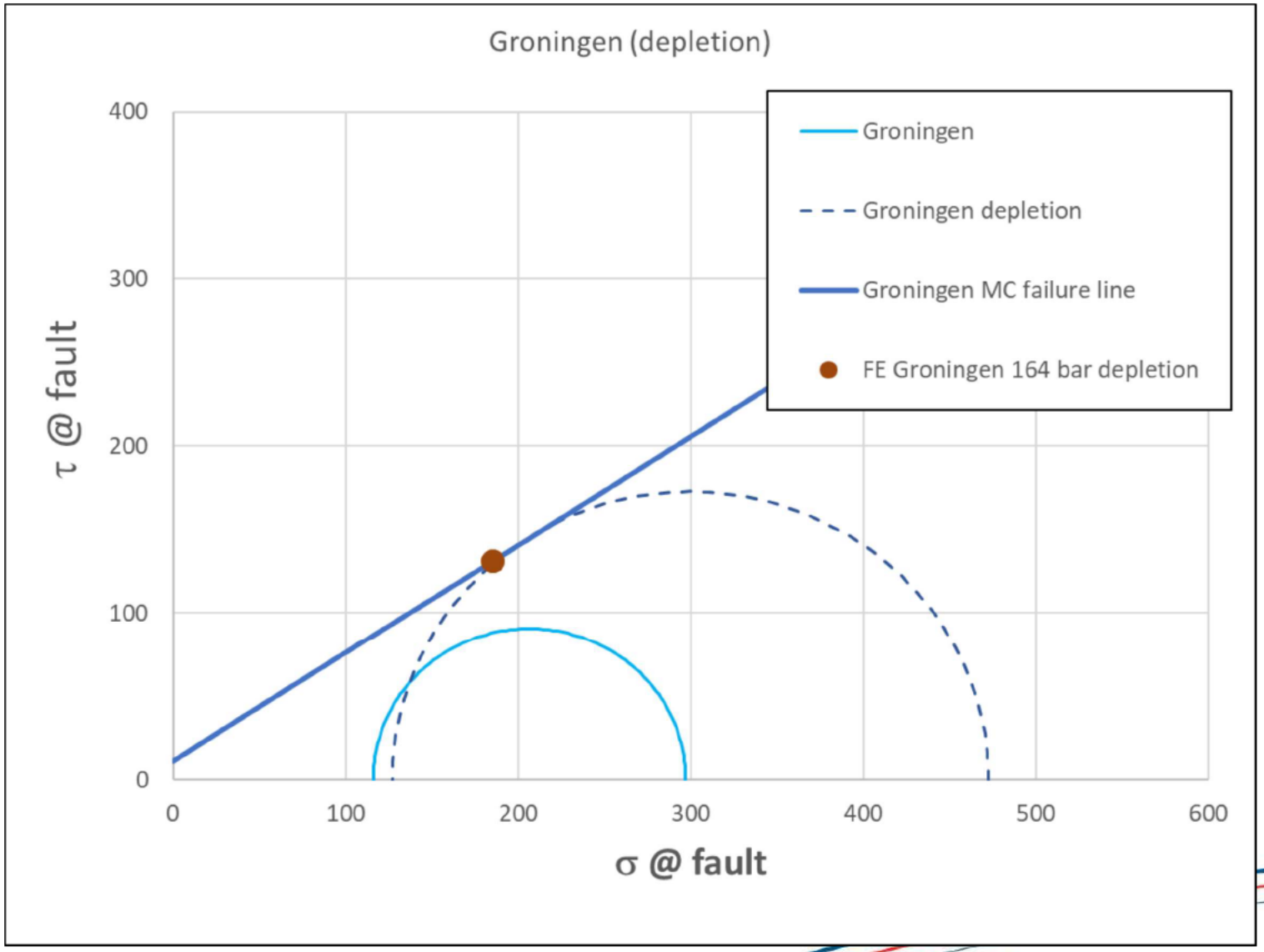
Groningen Depletion



Groningen model matches expected results in terms of timing, depletion and magnitude



Groningen Depletion: Mohr Coulomb



Finite Element: HAL Model

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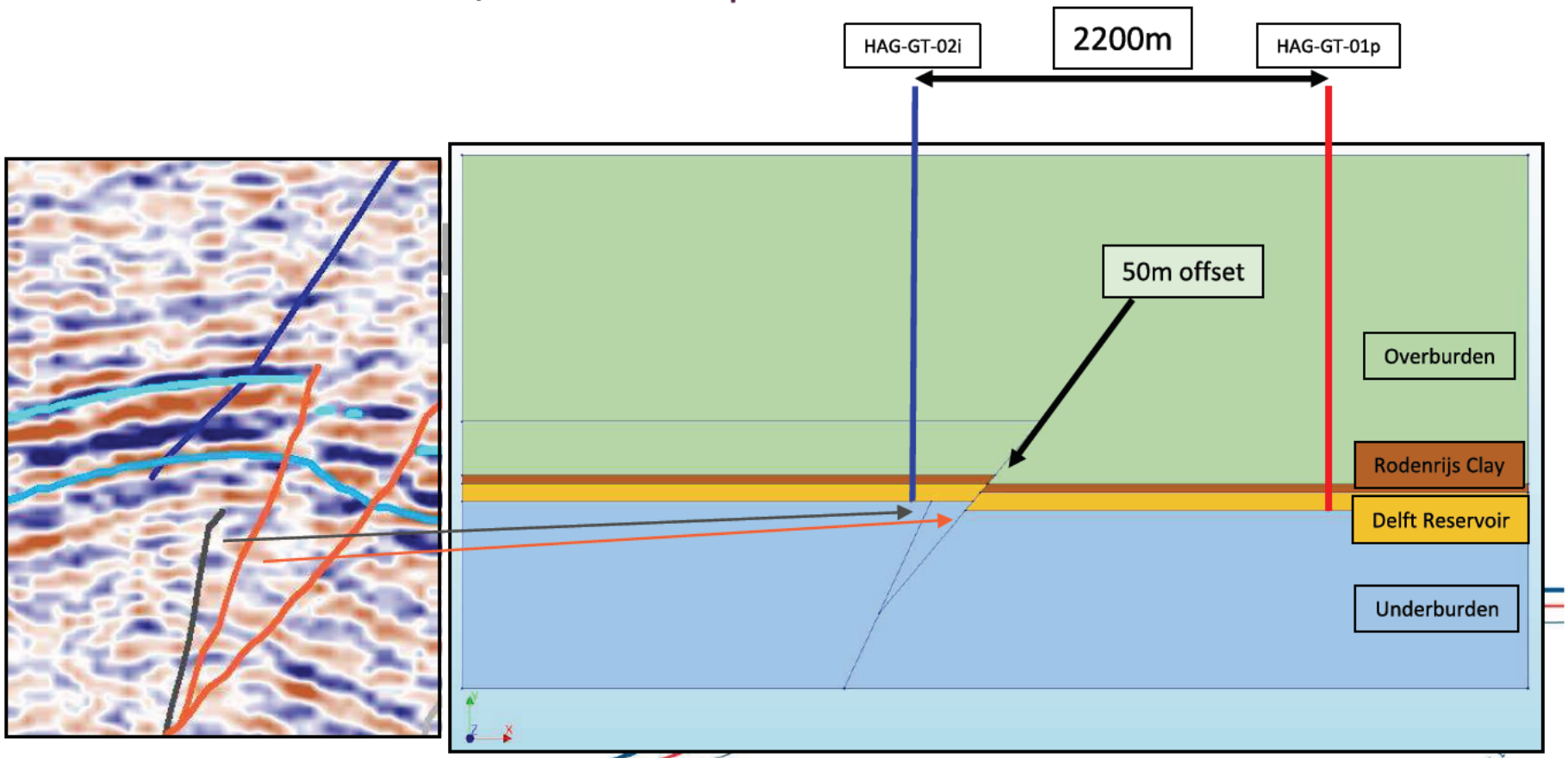
HAL Finite Element Model

- The two mapped faults were implemented in the model
  - 70° dipping fault below the reservoir
  - 50° dipping fault in the reservoir
- 50m offset was used as a most conservative scenario
- Reservoir is 100m thick, shale on top is 50m



HAL Finite Element Model

Production parameters: expected
Fault parameters: worst case
Reservoir parameters: conservative

- As base case a conservative scenario was used
  - Most critical fault azimuth (e.g. $\sigma_1 - \sigma_3$ Mohr Circle)
  - 50m offset along fault (expected: 25m)
  - Young's Modulus at 10 Gpa (expected: 3 GPa)
  - Poisson's ratio at 0.3 (expected: 0.25)
  - Flow through the fault

- 5 Models for HAL under these conservative conditions
  - Hypothetical depletion
  - Business Case Scenario
  - Maximum Business Case Scenario
  - Impermeable fault scenario
  - High-skin scenario

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Finite Element: Hypothetical depletion case HAL

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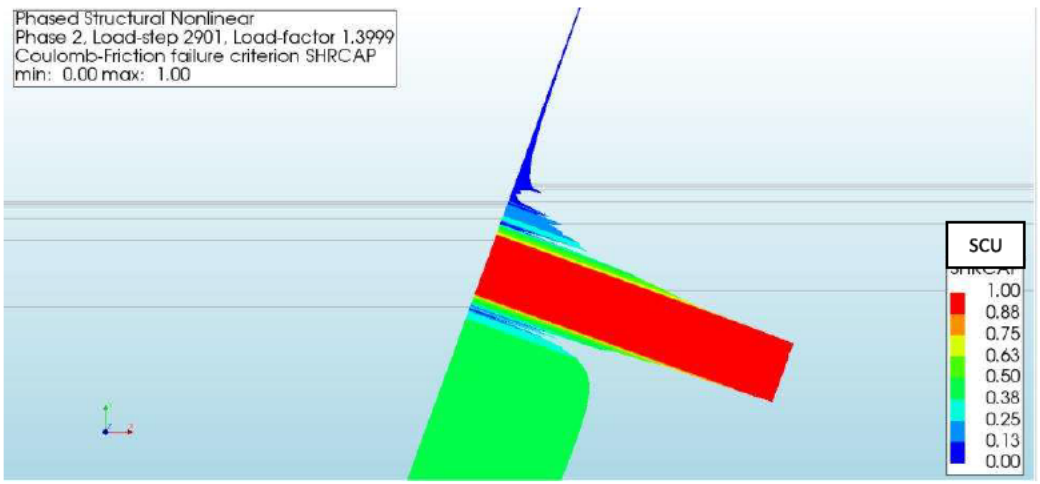
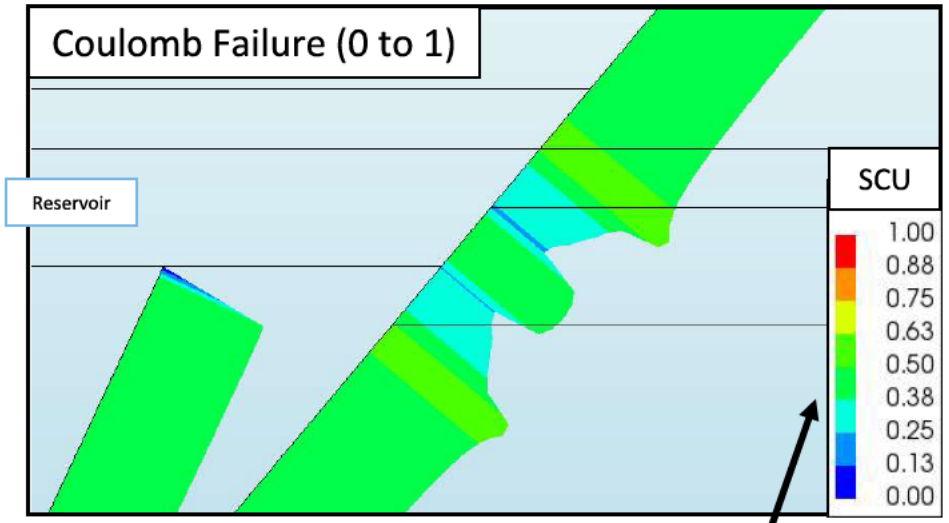
Hypothetical depletion HAL: **180** bar

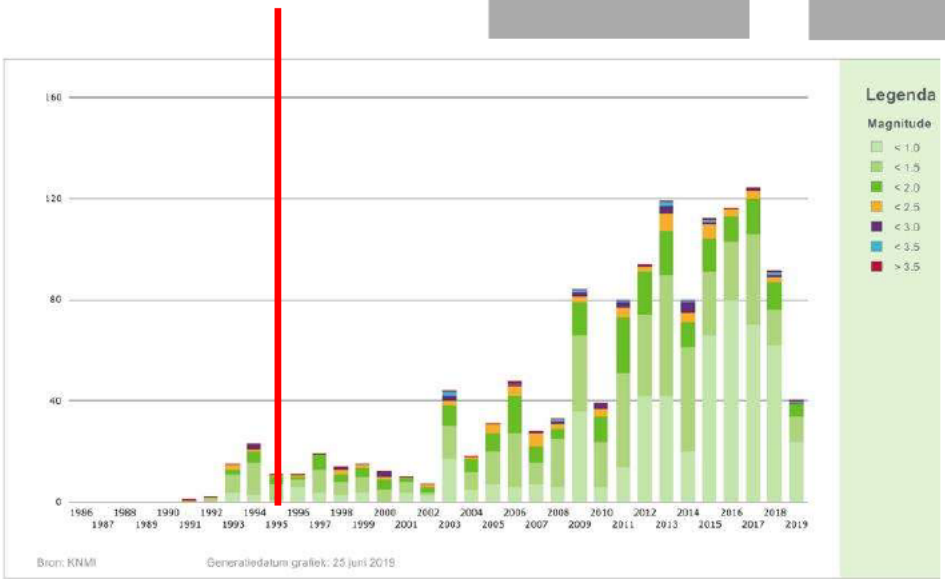
Groningen case: failure



HAL case: far from failure



Distance to coulomb failure.
A value of **1** is coulomb failure.



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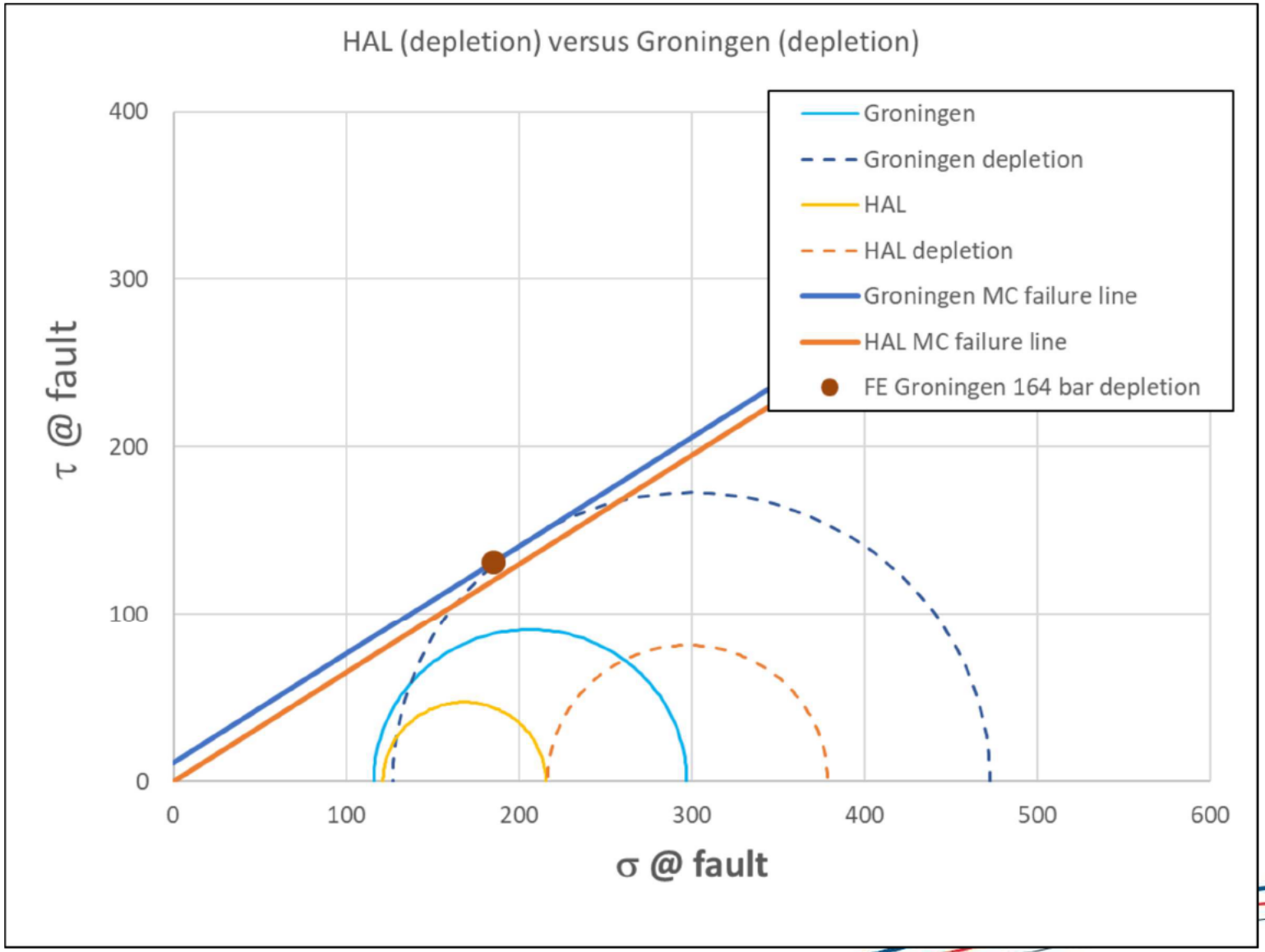
Depletion in HAL vs Groningen: Mohr Coulomb



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Finite Element scenarios HAL

	Business Case	Maximum Business Case	Impermeable Fault	Skin model
Flowrate	165/100 m^3/hr Variable	165 m^3/hr All year	Unrealistic	165 m^3/hr All year
Resulting pressure increase	5 bar	25 bar*	25 bar	60 bar
Temperature	45°/57°/63° Variable	45° All year	45° All year	45° All year

**For the Maximum Business Case scenario, a conservative permeability in the reservoir is used. This results in a higher injection pressure in the reservoir.*

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Injection pressure

Business Case Scenario

Doublet Calculator 1.4.3 Result Table

probabilistic plots | fingerprinting | export base case details

file: ... tation & Reporting\DoubletCalc(from 1437)\hal_sra_winningsvergunning_From_Hydreco_1009.xml

Geotechnics (Input)

Property	min	median	max
aquifer permeability (mD)	500.0	1400.0	2300.0
aquifer net to gross (-)	0.8	0.86	0.9
aquifer gross thickness (m)	100.0	112.0	120.0
aquifer top at producer (m TVD)	1998.0	2220.0	2442.0
aquifer top at injector (m TVD)	1587.0	1763.0	1939.0
aquifer water salinity (ppm)	100000.0	120000.0	140000.0

Property	value
number of simulation runs (-)	1000.0
aquifer kh/kv ratio (-)	5.0
surface temperature (°C)	10.0
geothermal gradient (°C/m)	0.0308
[mid aquifer temperature producer (°C)]	80.0
inital aquifer pressure at producer (bar)]	0.0
[initial aquifer pressure at injector (bar)]	0.0
exit temperature heat exchanger (°C)	45.0
distance wells at aquifer level (m)	2200.0
pump system efficiency (-)	0.6
production pump depth (m)	600.0
pump pressure difference (bar)	33.0
outer diameter producer (inch)	6.0
skin producer (-)	20.0
skin due to penetration angle p (-)	0.0
pipe segment sections p (m AH)	600.0,1110.0,2422.0,2673.0
pipe segment depth p (m TVD)	600.0,1078.0,2095.0,2275.0
pipe inner diameter p (inch)	6.37,9.95,6.36,3.92
pipe roughness p (milli-inch)	1.8,1.8,1.8,1.8
outer diameter injector (inch)	6.0
skin injector (-)	0.8
skin due to penetration angle i (-)	0.0
pipe segment sections i (m AH)	150.0,1096.0,2117.0,2314.0
pipe segment depth i (m TVD)	150.0,1063.0,1750.0,1887.0

Geotechnics (Output)

Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	85.18	133.87	181.7
mass flow (kg/s)	42.23	46.42	51.78
pump volume flow (m³/h)	143.5	163.9	175.5
required pump power (kW)	219.3	250.5	268.1
geothermal power (MW)	4.86	5.77	6.61
COP (kW/kW)	20.8	23.2	25.7
aquifer pressure at producer (bar)	218.98	232.21	245.75
aquifer pressure at injector (bar)	181.56	191.83	202.0
pressure difference at producer (bar)	7.22	9.18	12.44
pressure difference at injector (bar)	3.96	5.05	6.92
aquifer temperature at producer * (°C)	76.23	80.0	83.75
temperature at heat exchanger (°C)	74.38	77.94	81.54

base case (median value inputs)	value
aquifer kH net (Dm)	134.85
mass flow (kg/s)	48.57
pump volume flow (m³/h)	164.7
required pump power (kW)	251.6
geothermal power (MW)	5.86
COP (kW/kW)	23.3
aquifer pressure at producer (bar)	232.22
aquifer pressure at injector (bar)	191.62
pressure difference at producer (bar)	9.11
pressure difference at injector (bar)	5.01
aquifer temperature at producer * (°C)	80.0
temperature at heat exchanger (°C)	77.99
pressure at heat exchanger (bar)	6.11

* @ mid aquifer depth

Maximum Business Case Scenario

Doublet Calculator 1.4.3 Result Table

probabilistic plots | fingerprinting | export base case details

file: ... & Reporting\DoubletCalc(from 1437)\hal_sra_winningsvergunning_from_hydreco_1009_280md.xml

Geotechnics (Input)

Property	min	median	max
aquifer permeability (mD)	140.0	280.0	420.0
aquifer net to gross (-)	0.8	0.86	0.9
aquifer gross thickness (m)	100.0	112.0	120.0
aquifer top at producer (m TVD)	1998.0	2220.0	2442.0
aquifer top at injector (m TVD)	1587.0	1763.0	1939.0
aquifer water salinity (ppm)	100000.0	120000.0	140000.0

Property	value
number of simulation runs (-)	1000.0
aquifer kh/kv ratio (-)	5.0
surface temperature (°C)	10.0
geothermal gradient (°C/m)	0.0308
[mid aquifer temperature producer (°C)]	80.0
inital aquifer pressure at producer (bar)]	0.0
[initial aquifer pressure at injector (bar)]	0.0
exit temperature heat exchanger (°C)	45.0
distance wells at aquifer level (m)	2200.0
pump system efficiency (-)	0.6
production pump depth (m)	600.0
pump pressure difference (bar)	90.0
outer diameter producer (inch)	6.0
skin producer (-)	20.0
skin due to penetration angle p (-)	0.0
pipe segment sections p (m AH)	600.0,1110.0,2422.0,2673.0
pipe segment depth p (m TVD)	600.0,1078.0,2095.0,2275.0
pipe inner diameter p (inch)	6.37,9.95,6.36,3.92
pipe roughness p (milli-inch)	1.8,1.8,1.8,1.8
outer diameter injector (inch)	6.0
skin injector (-)	0.8
skin due to penetration angle i (-)	0.0
pipe segment sections i (m AH)	150.0,1096.0,2117.0,2314.0
pipe segment depth i (m TVD)	150.0,1063.0,1750.0,1887.0

Geotechnics (Output)

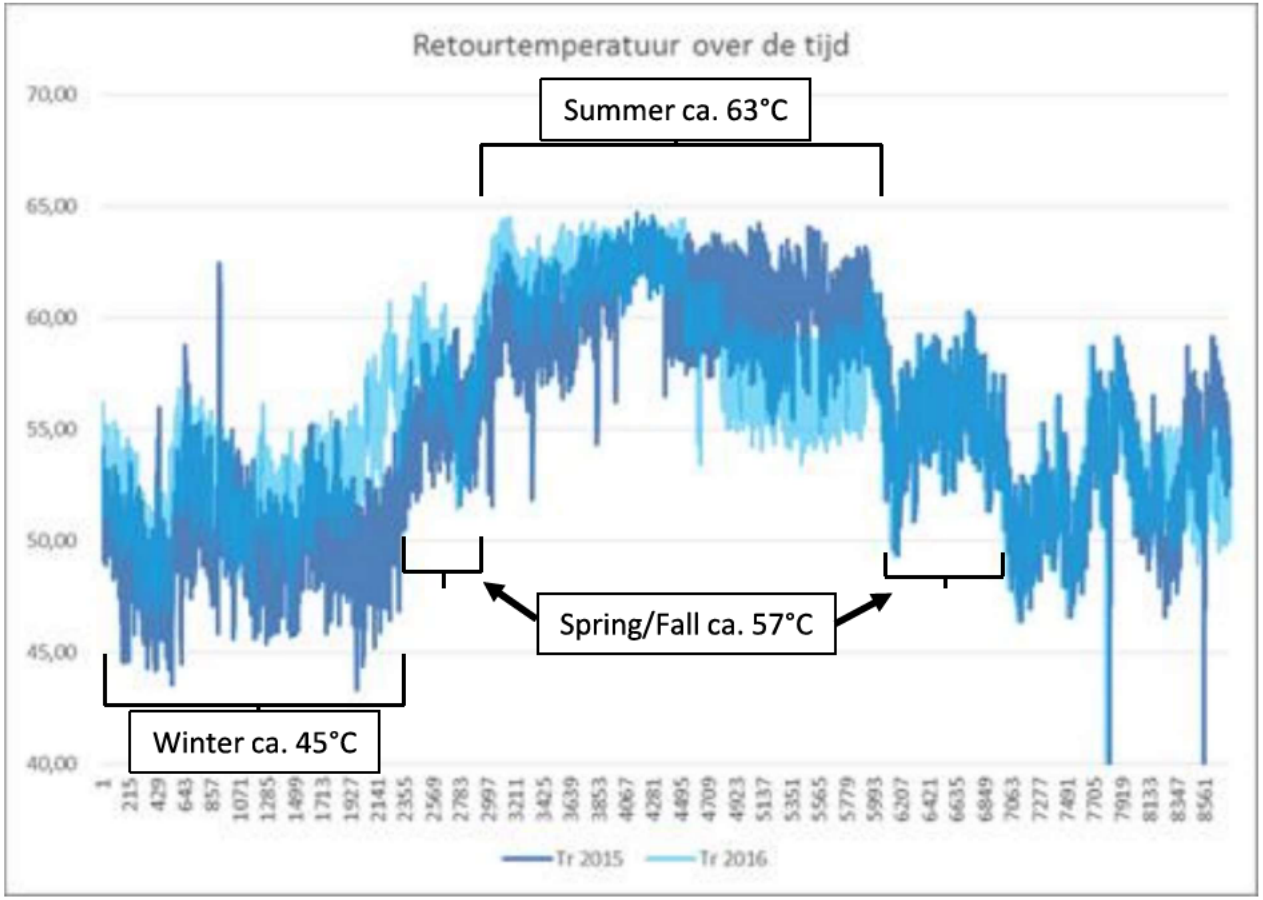
Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	19.3	26.64	34.32
mass flow (kg/s)	39.01	48.32	56.39
pump volume flow (m³/h)	132.1	163.7	191.3
required pump power (kW)	550.5	682.2	797.2
geothermal power (MW)	4.5	5.8	7.08
COP (kW/kW)	7.6	8.5	9.4
aquifer pressure at producer (bar)	219.12	232.25	245.79
aquifer pressure at injector (bar)	181.87	191.83	202.1
pressure difference at producer (bar)	41.28	46.17	51.07
pressure difference at injector (bar)	22.69	25.31	28.06
aquifer temperature at producer * (°C)	76.28	80.0	83.79
temperature at heat exchanger (°C)	74.38	77.91	81.56

base case (median value inputs)	value
aquifer kH net (Dm)	26.97
mass flow (kg/s)	48.92
pump volume flow (m³/h)	165.9
required pump power (kW)	691.5
geothermal power (MW)	5.91
COP (kW/kW)	8.5
aquifer pressure at producer (bar)	232.22
aquifer pressure at injector (bar)	191.62
pressure difference at producer (bar)	45.91
pressure difference at injector (bar)	25.21
aquifer temperature at producer * (°C)	80.0
temperature at heat exchanger (°C)	78.01
pressure at heat exchanger (bar)	26.29

* @ mid aquifer depth

PANterra

Business Case Scenario HAL



Business Case Scenario HAL

- Injection pressure is matched to the
- Temperature is variable

[redacted]

Business Case Scenario HAL

[redacted]

[redacted]

[redacted]

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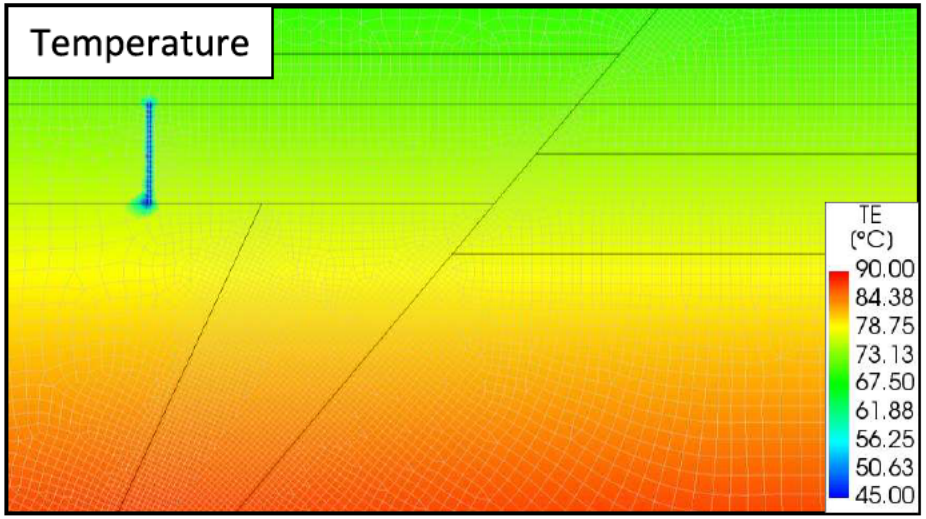
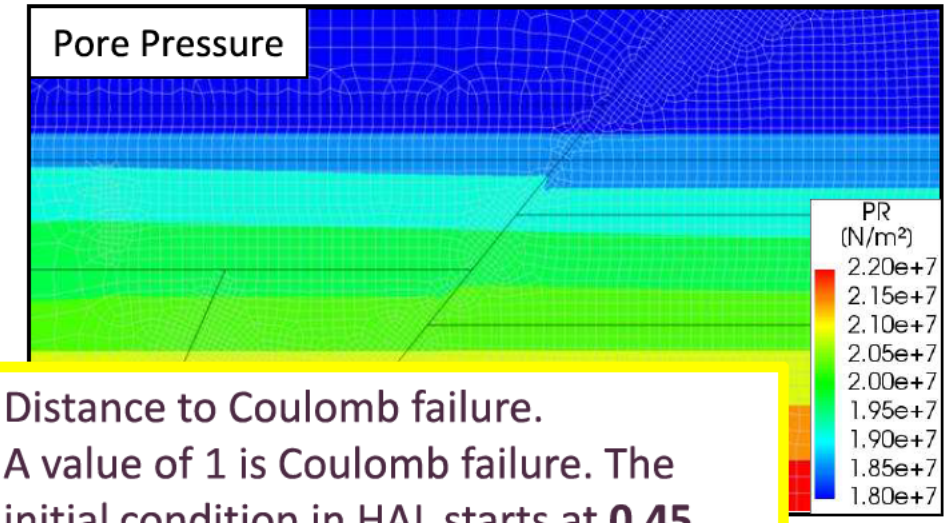
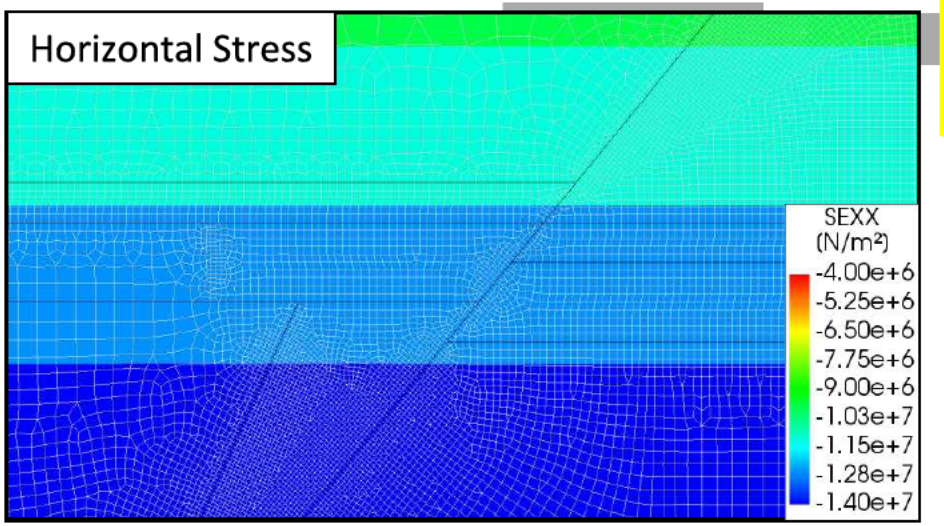
Business Case Scenario HAL

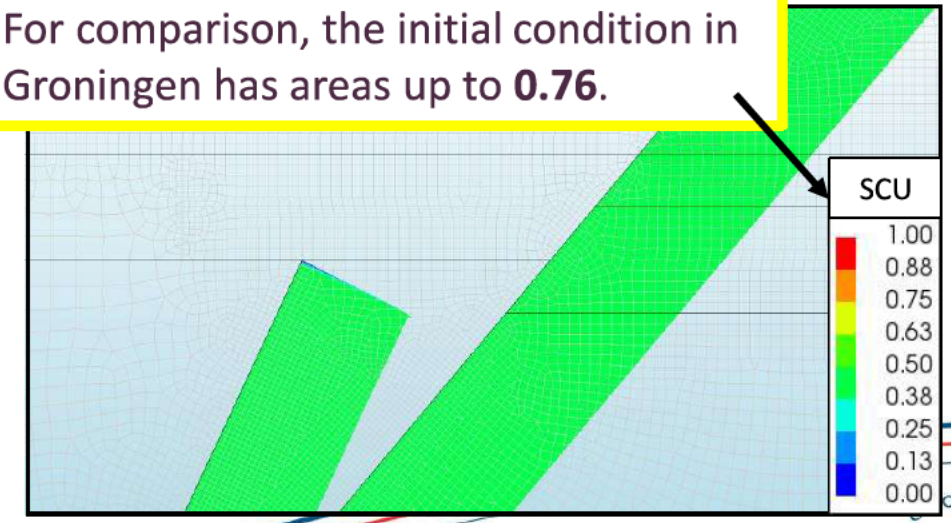
Time = 3 years







Distance to Coulomb failure.
A value of 1 is Coulomb failure. The initial condition in HAL starts at **0.45**.
For comparison, the initial condition in Groningen has areas up to **0.76**.



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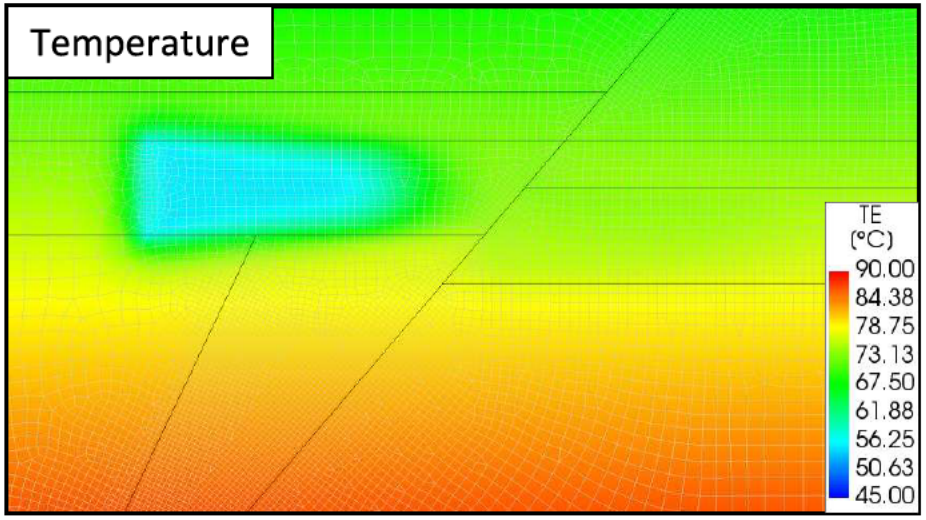
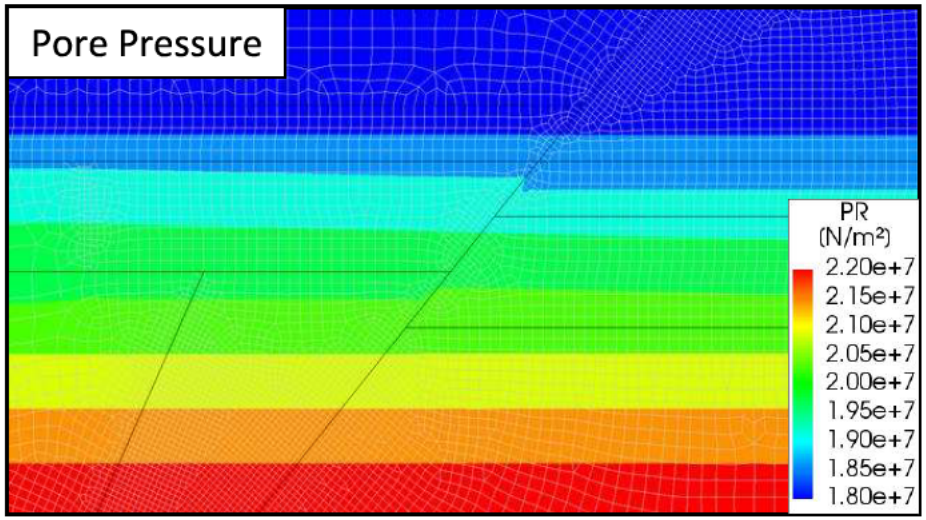
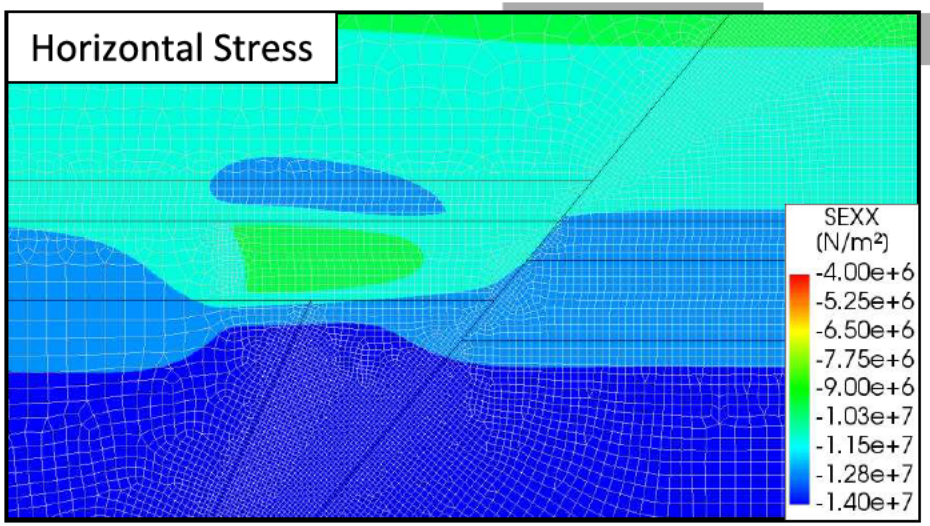
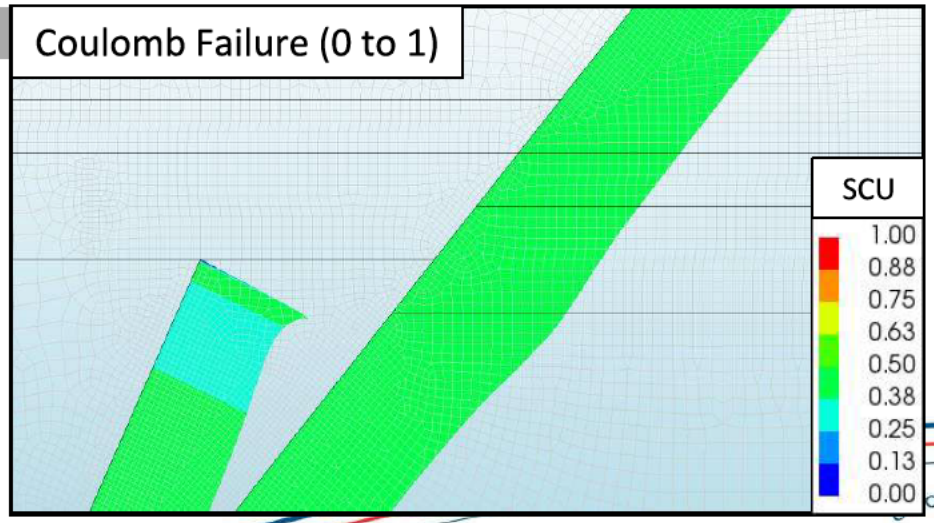
Business Case Scenario HAL

Time = 15 years









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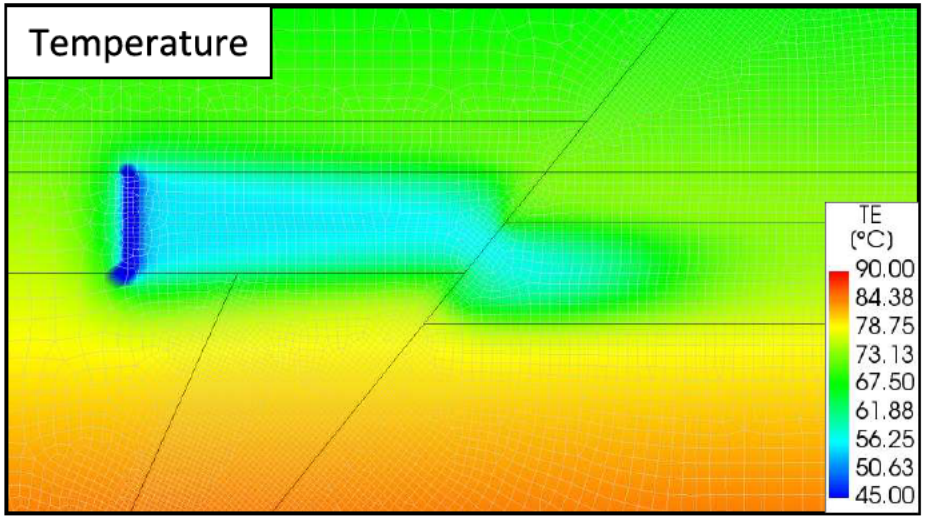
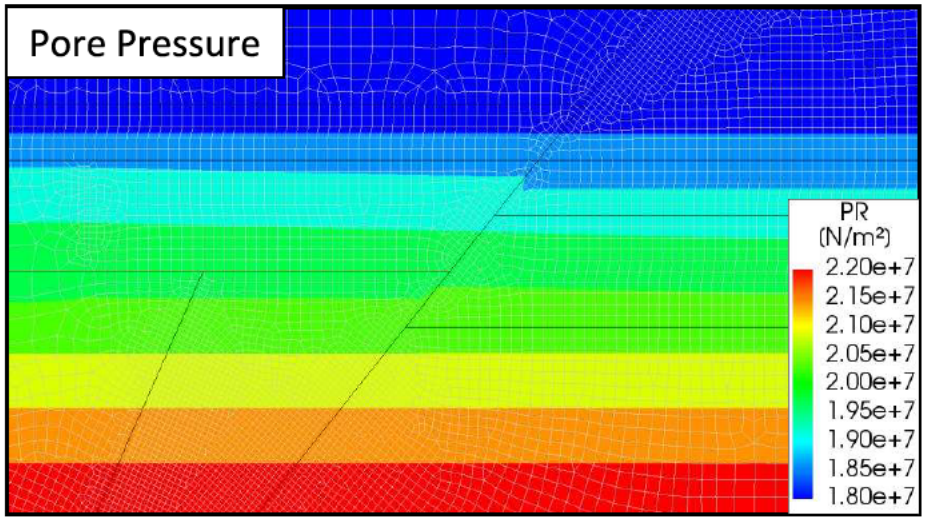
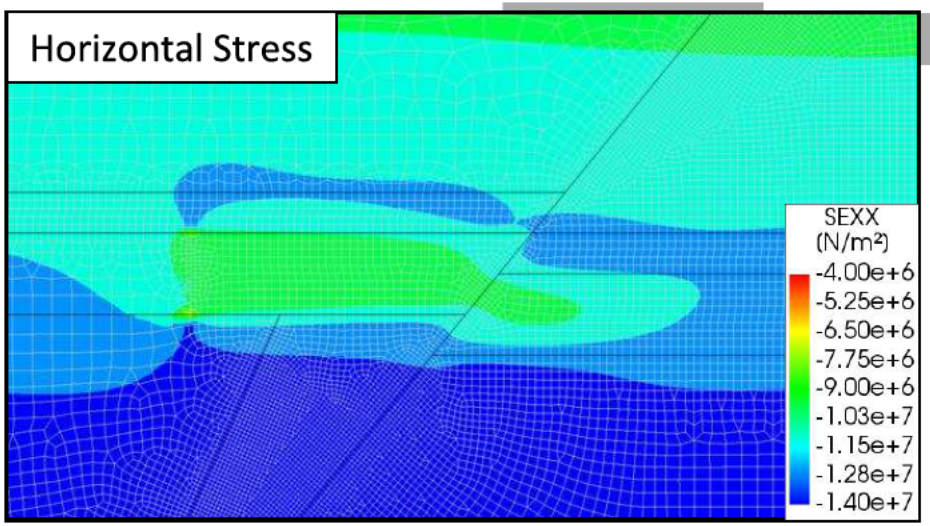
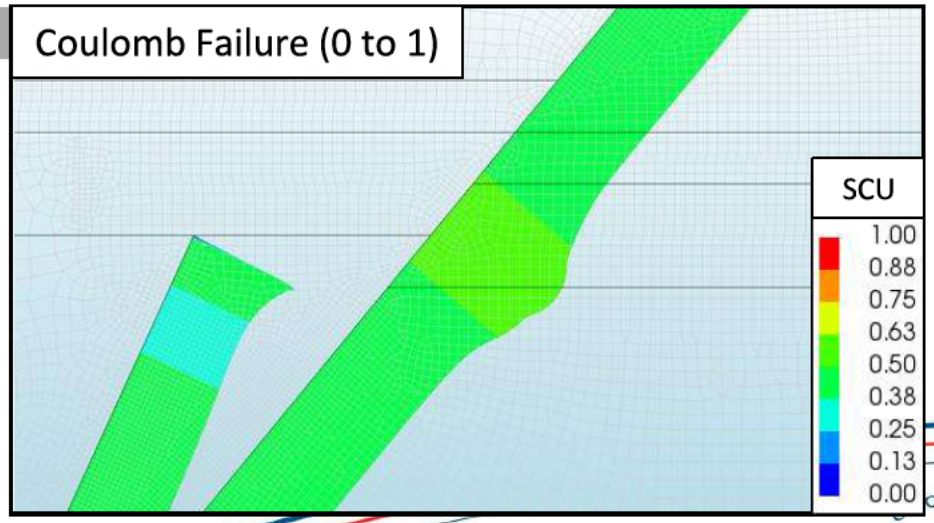
Business Case Scenario HAL

Time = 30 years









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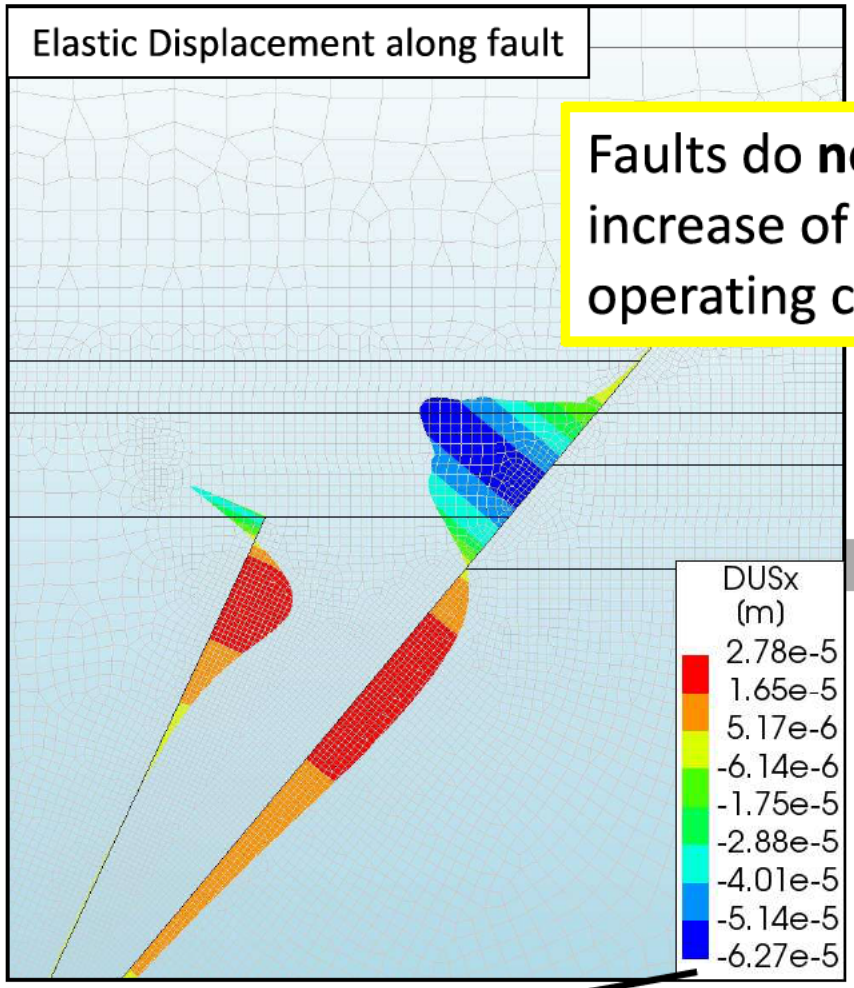
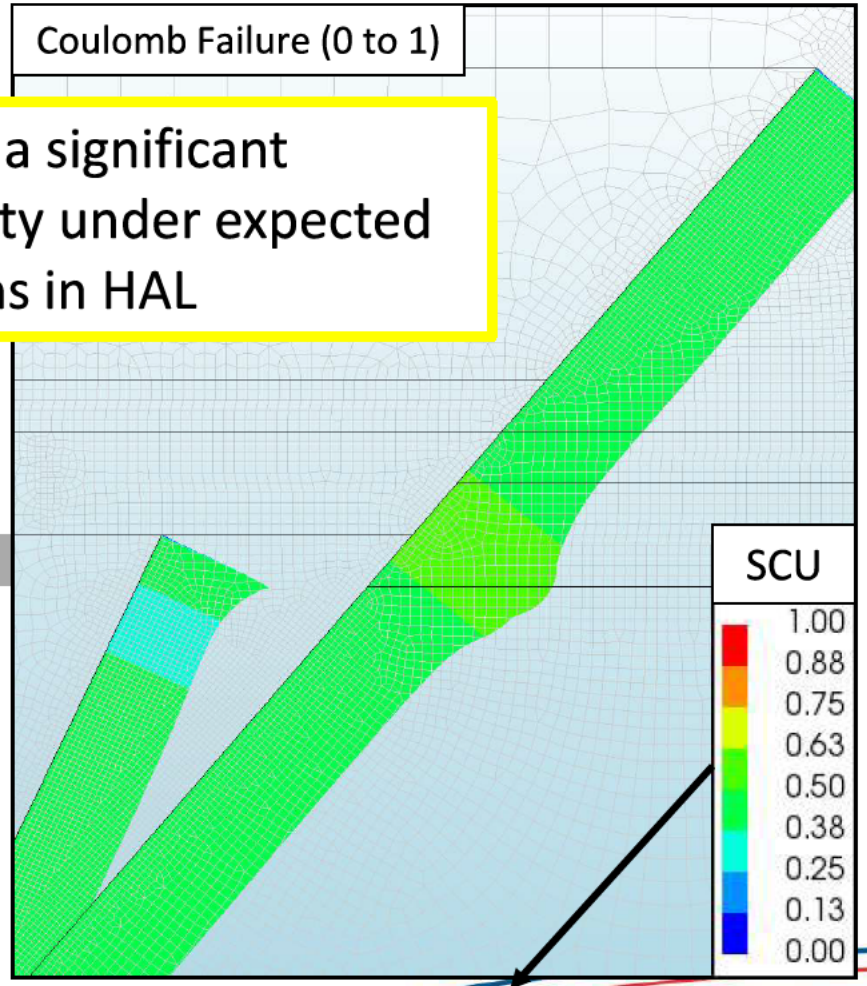
Business Case Scenario HAL

Time = 30 years





Faults do **not** show a significant increase of instability under expected operating conditions in HAL

60 micrometers

Max. SCU of 0.61

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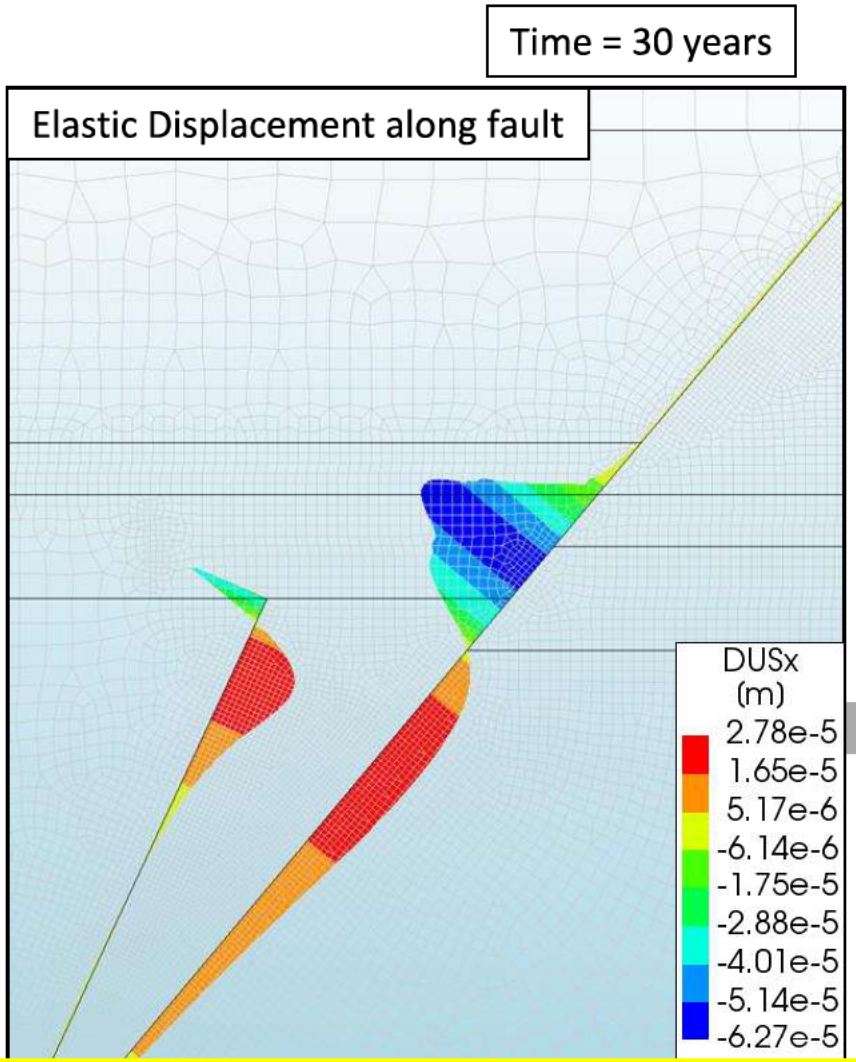
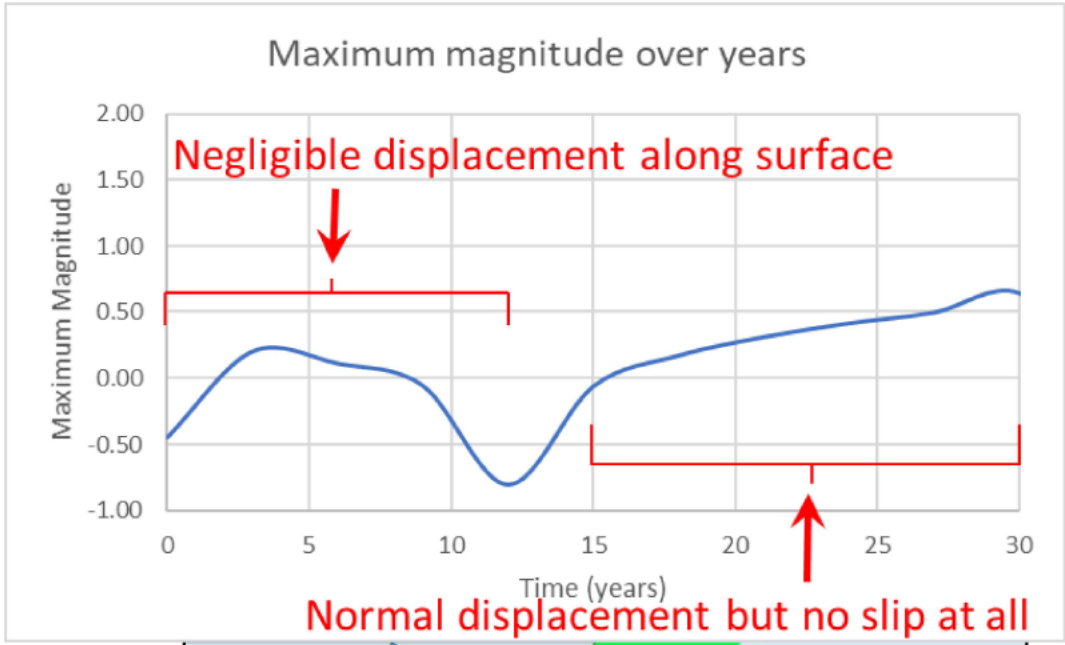
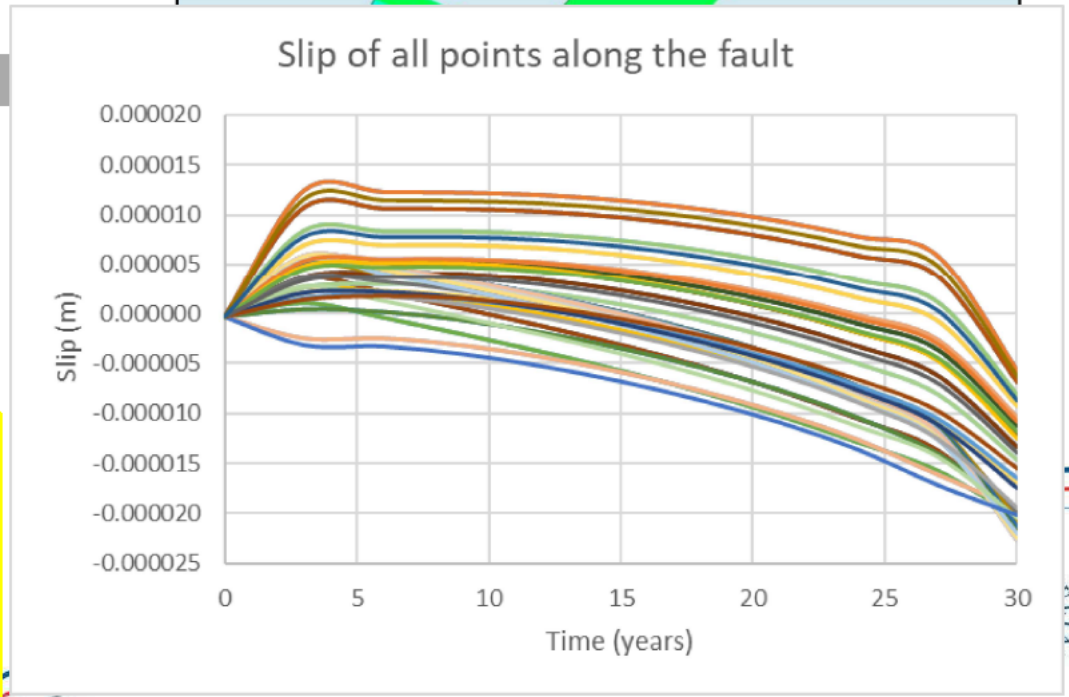
Business Case Scenario HAL





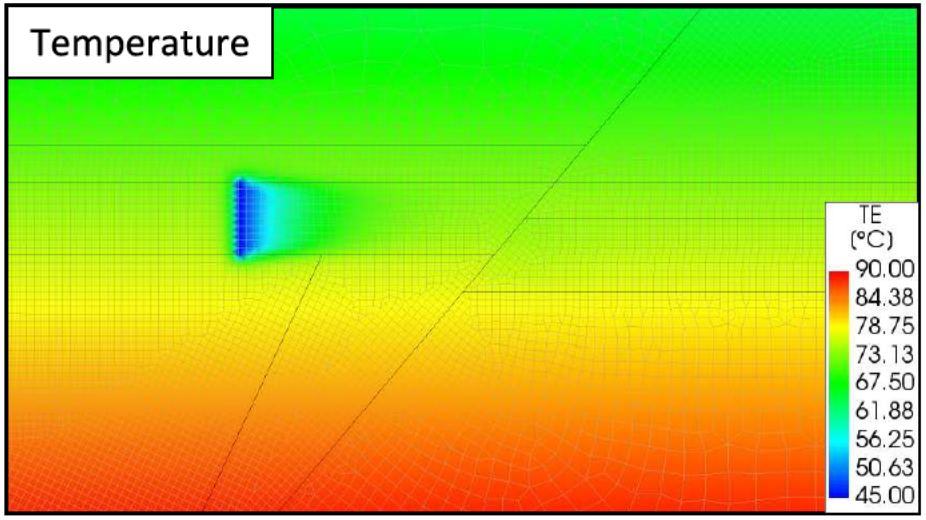


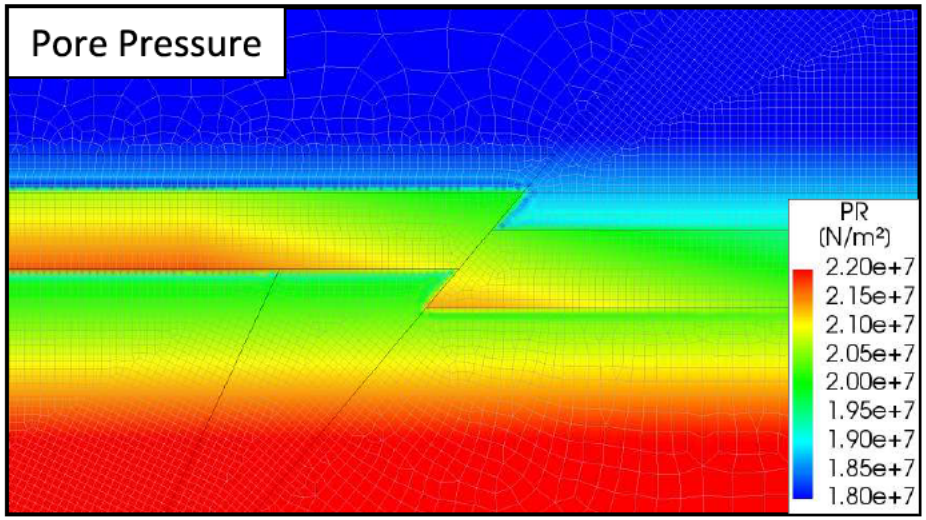
This is elastic displacement, not instantaneous slip.

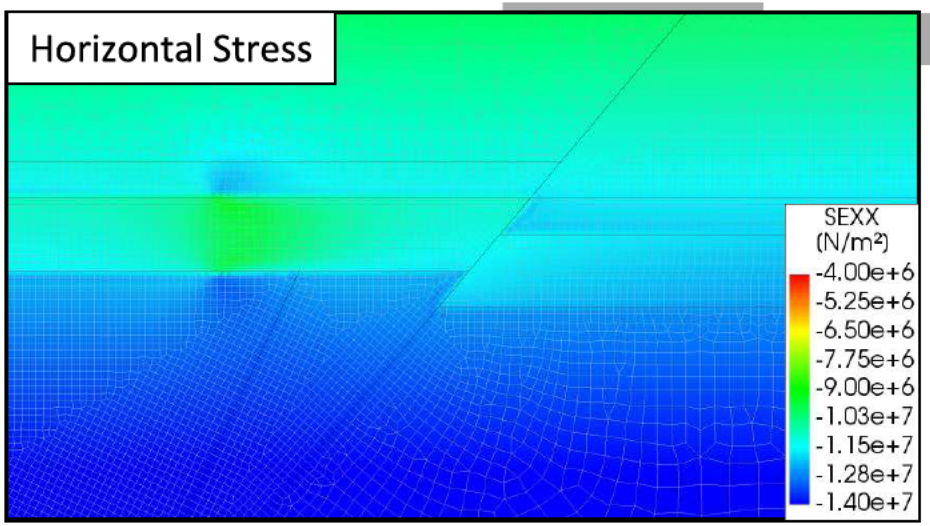
However, slip of in the order of 2/100th of a mm would have a **maximum** magnitude of **0.6**

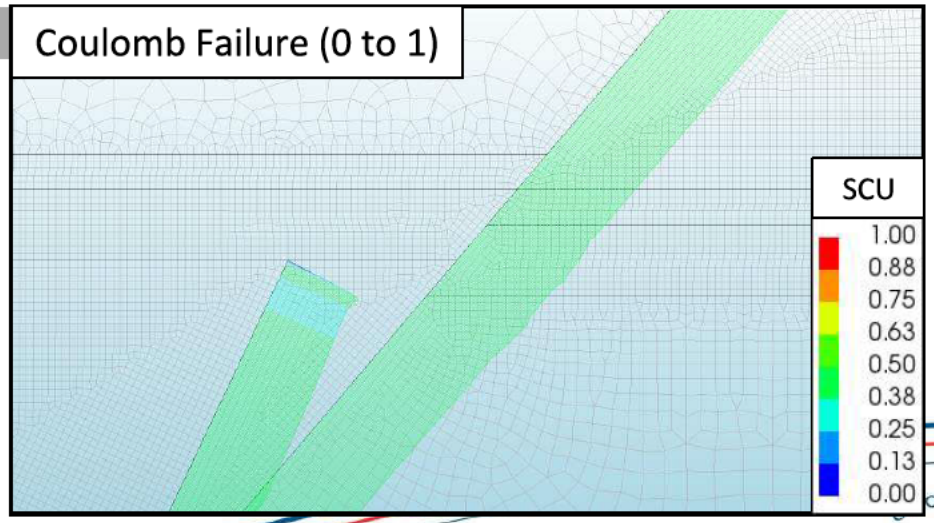
Maximum Business Case Scenario

Time = 3 years









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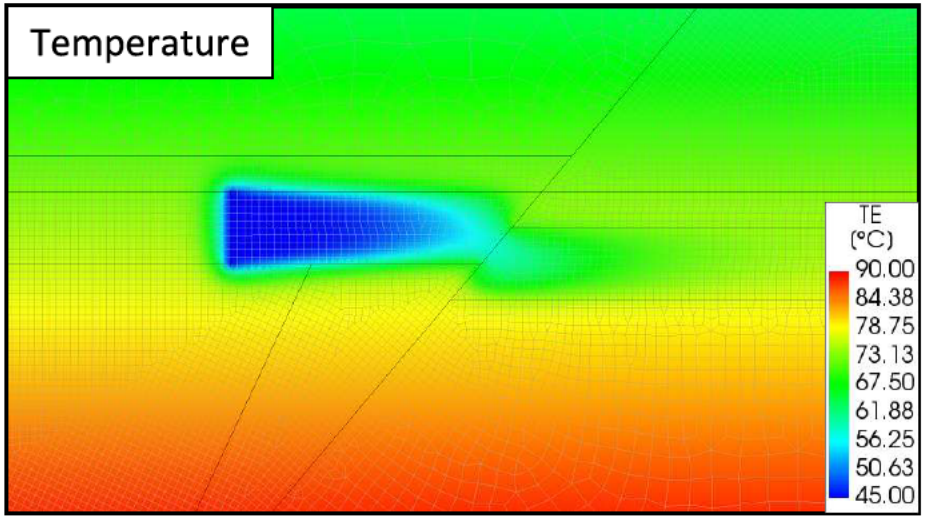
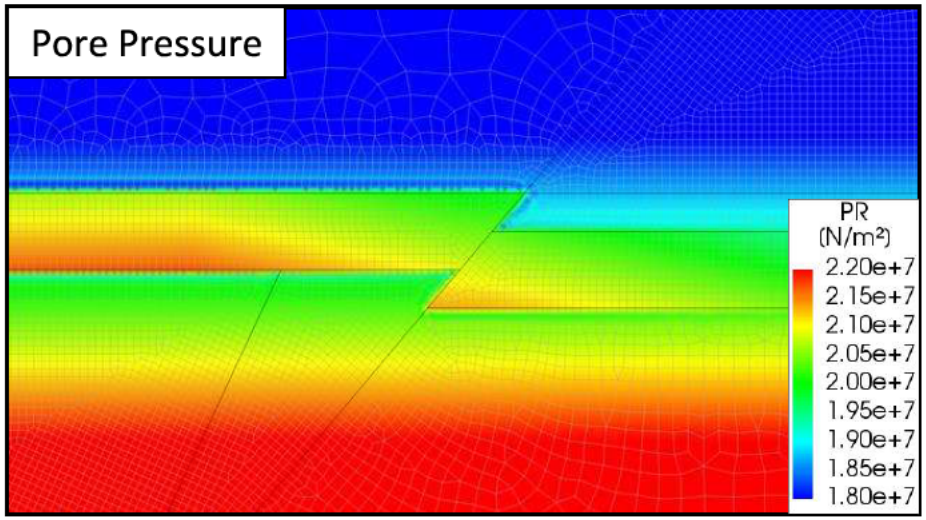
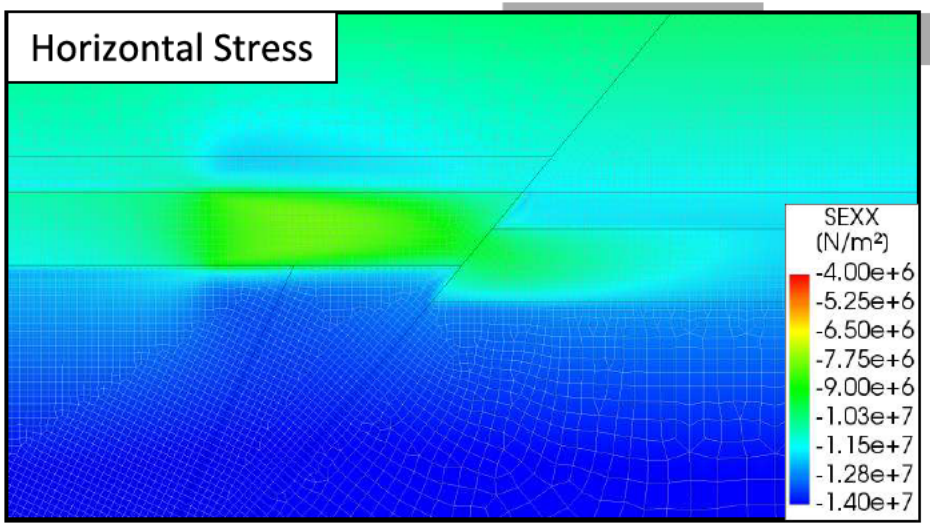
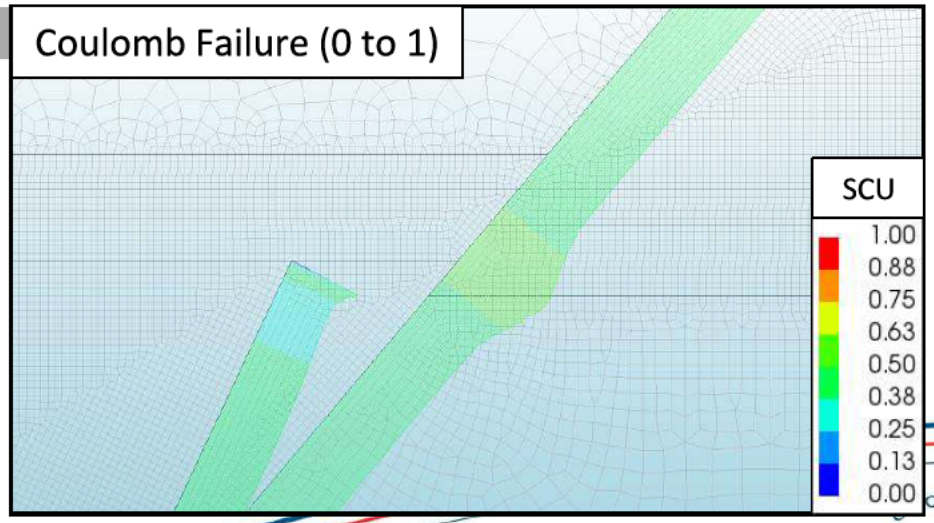
Maximum Business Case Scenario

Time = 15 years









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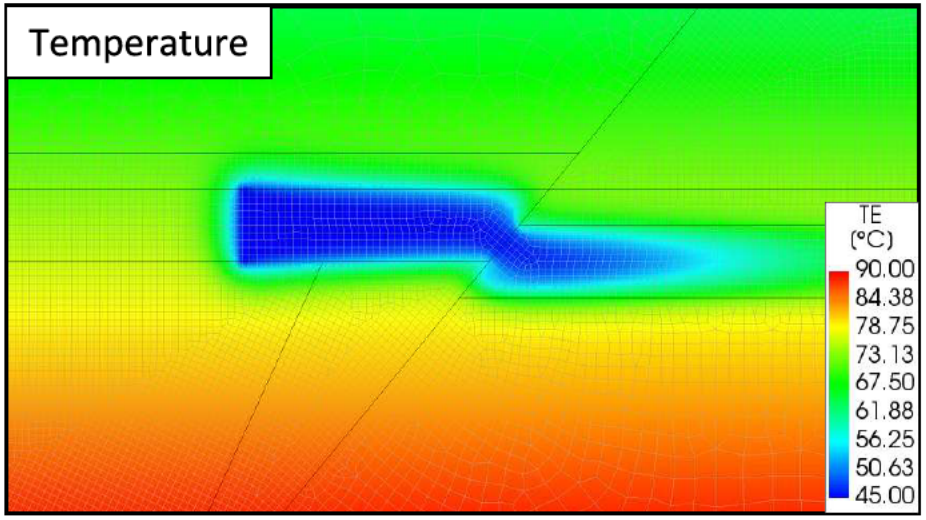
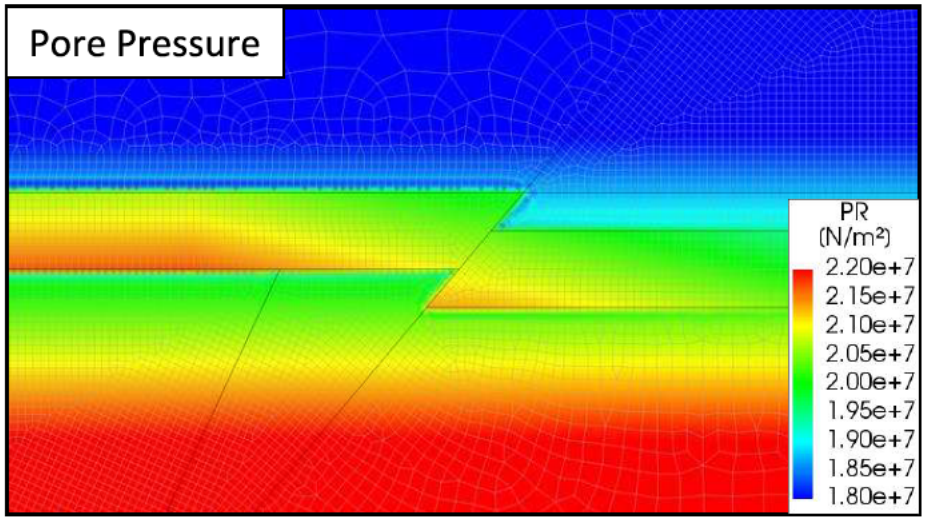
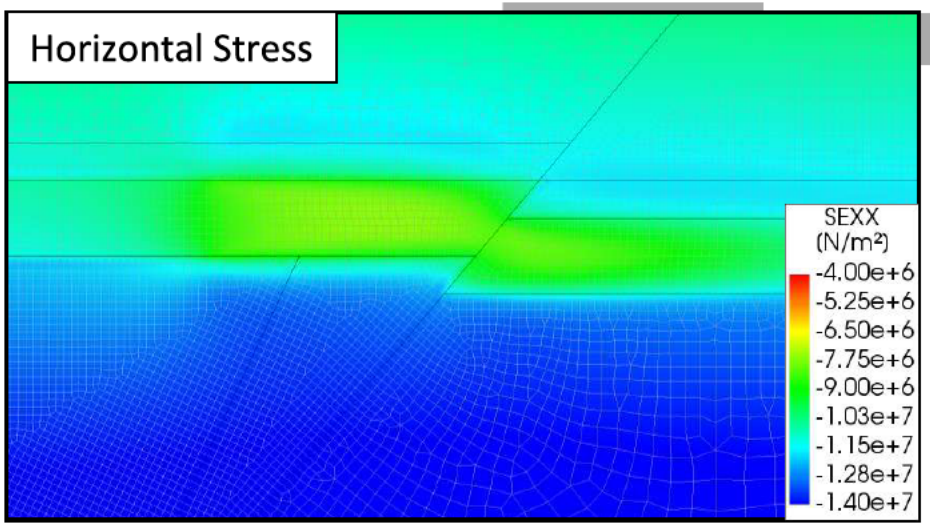
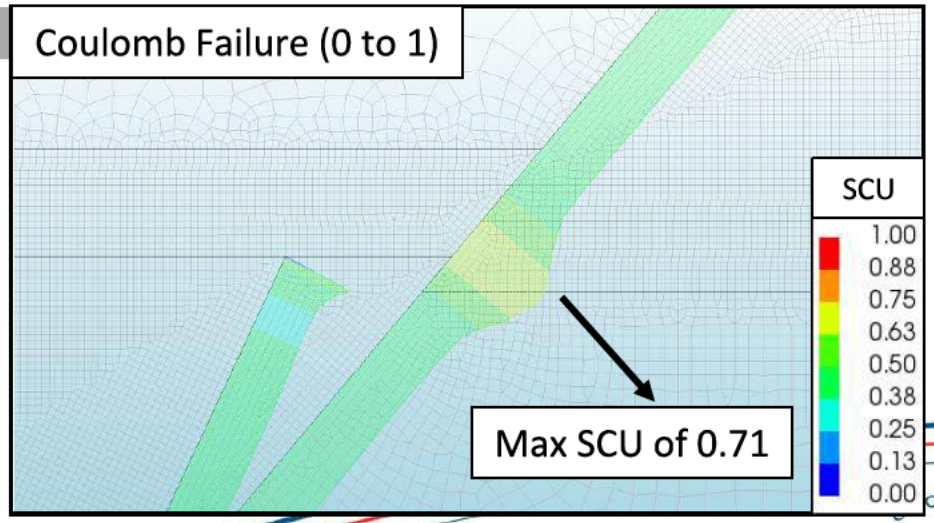
Maximum Business Case Scenario

Time = 30 years









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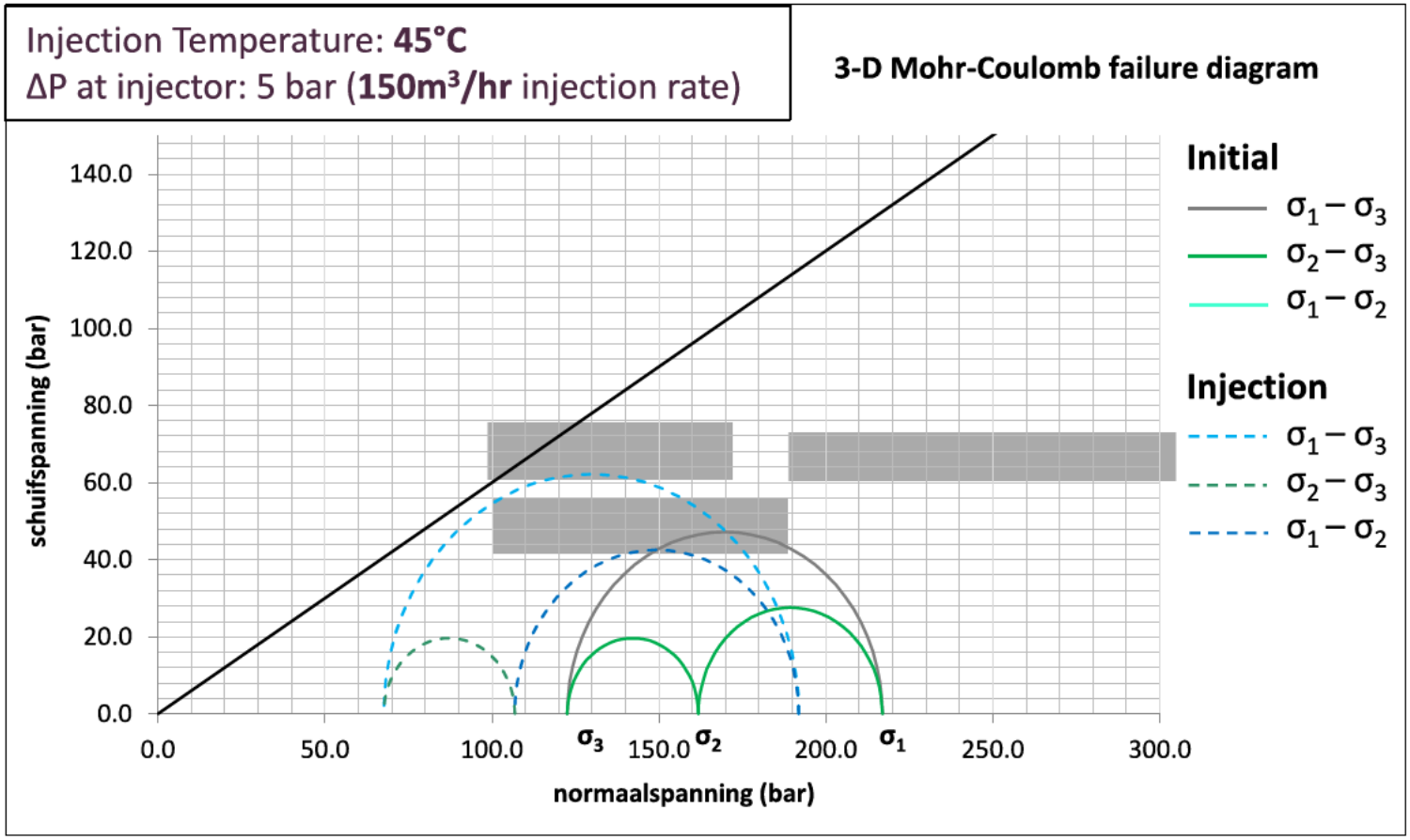
Maximum Business Case Scenario

- Situation after injection is closer to the failure line

Under the maximum possible business case, no failure is expected

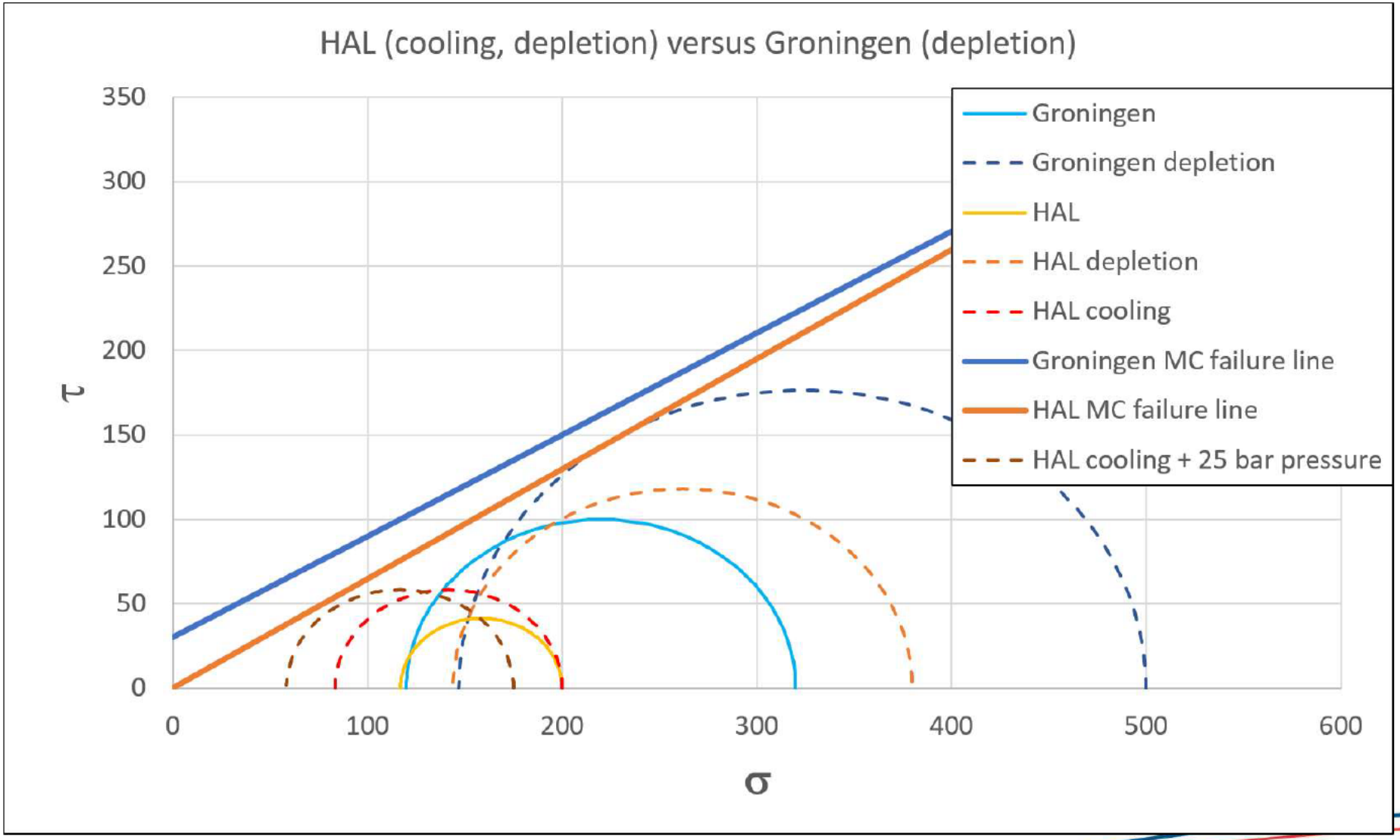
Injection Temperature: **45°C**
ΔP at injector: 5 bar (**150m³/hr** injection rate)



- Young's Modulus E = 10 GPa
- Poisson's ratio v = 0.3
- Thermal expansion coefficient $\alpha = 1 \cdot 10^{-5}$
- Frictioncoefficient $\mu = 0.6$
- $T_{reservoir} = 73°C$
- Re-injection temperature = 45°C (Winter scenario)
- Injection pressure = 25 bar
- **No cohesion assumed**

Production parameters: worst case (winter)
Fault parameters: worst case
Reservoir parameters: conservative

HAL cooling: Mohr Coulomb



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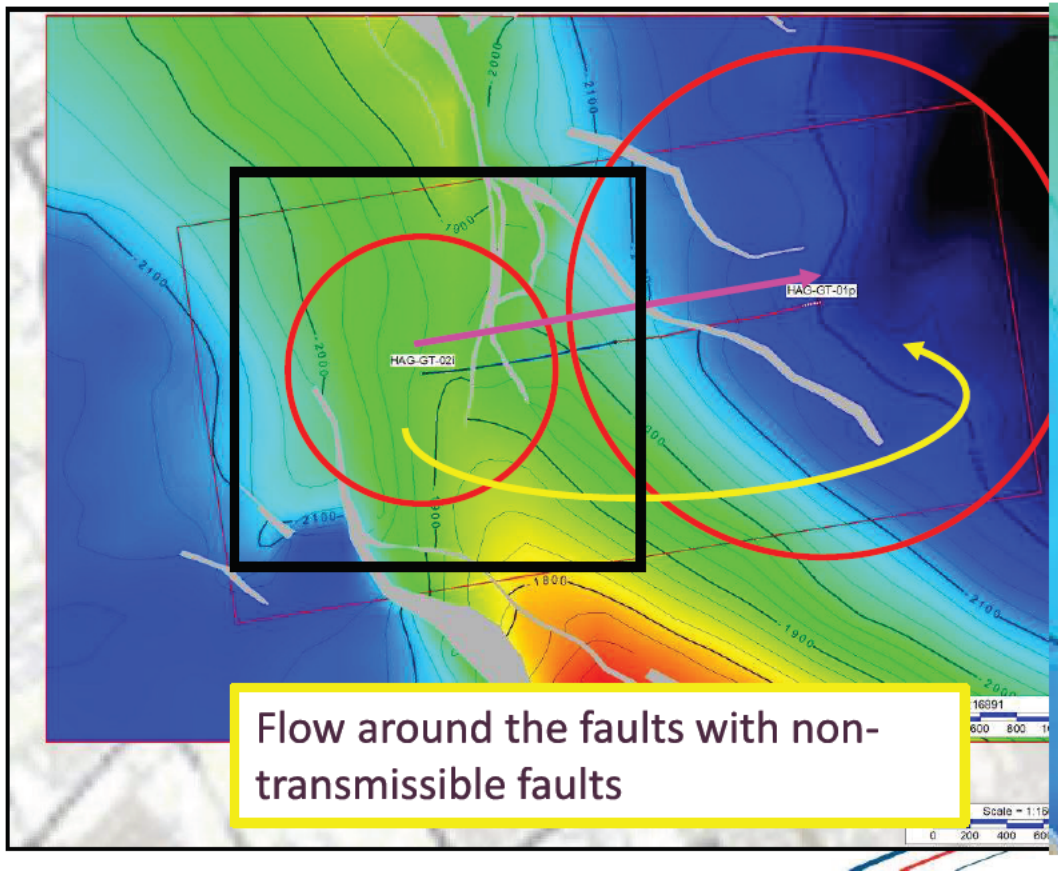
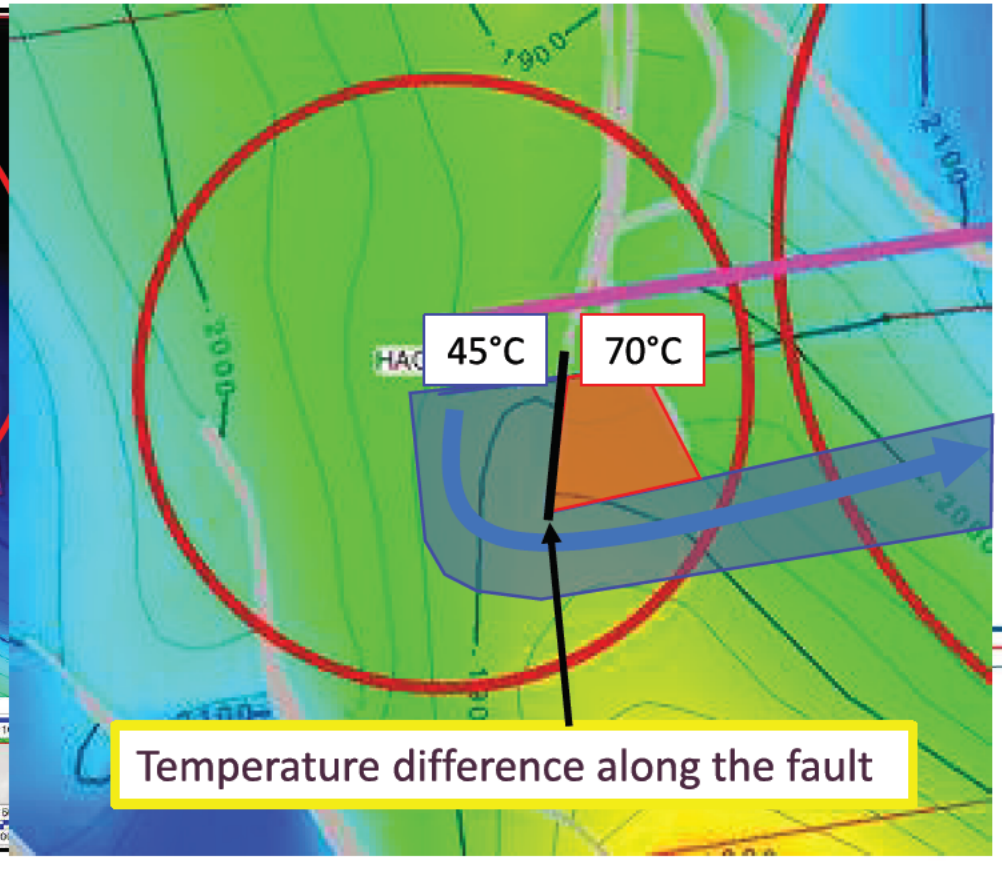
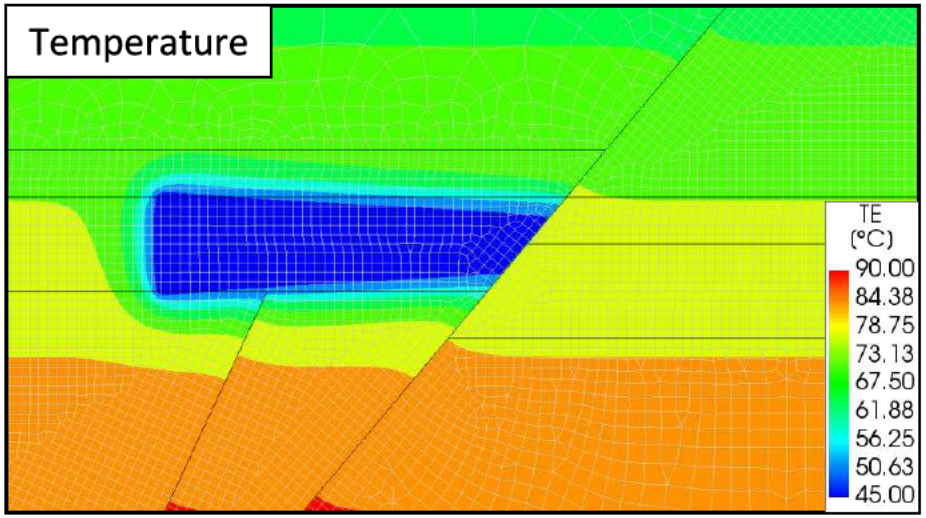
Finite element
Impermeable fault scenario

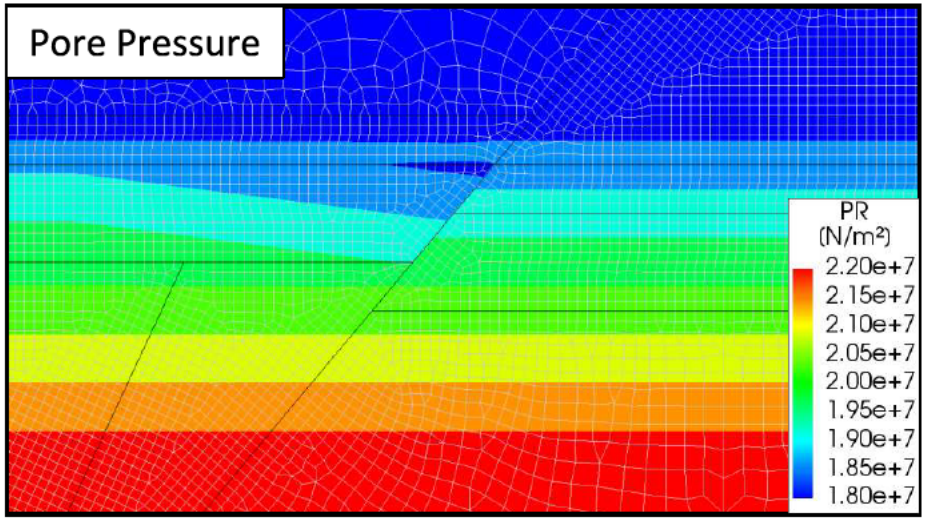
- Impermeable fault may have a large temperature and pressure difference along the fault
- The model was forced to come to this scenario as the temperature front is not expected to reach the fault
- To increase the temperature contrast, no temperature diffusion was allowed through the fault.

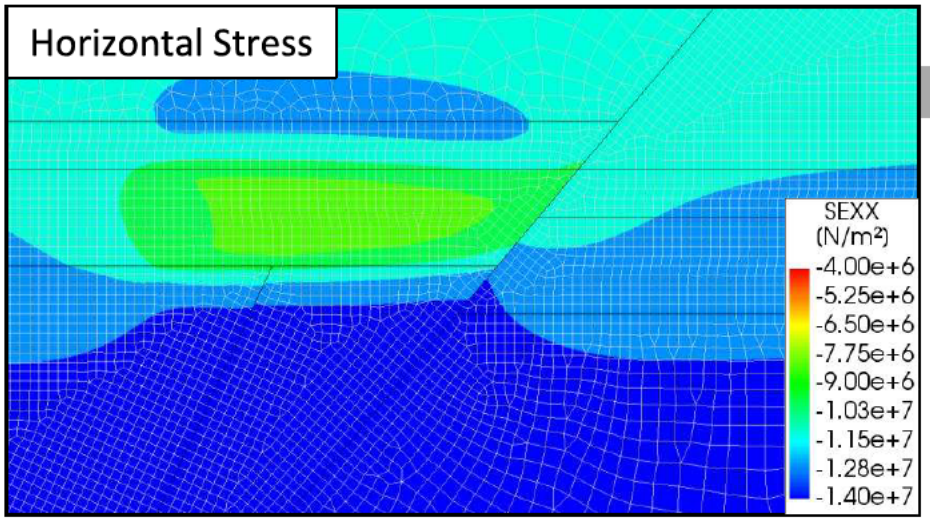


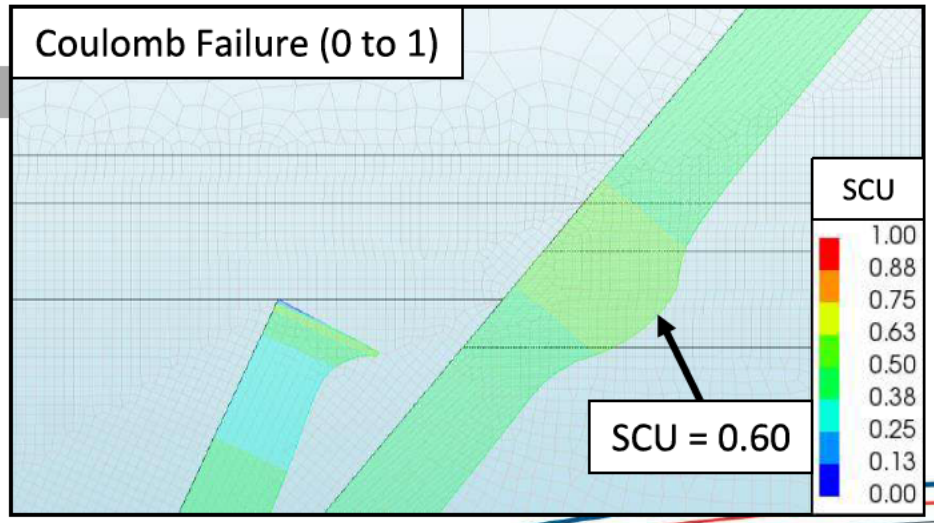


Impermeable fault scenario









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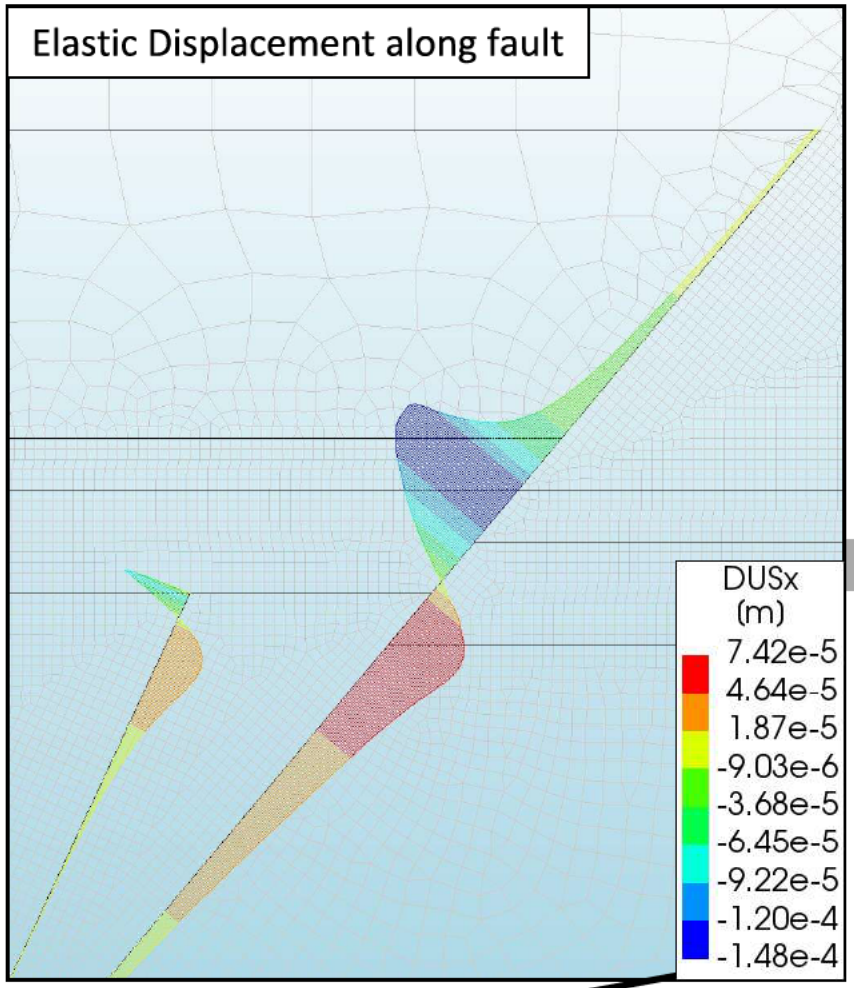
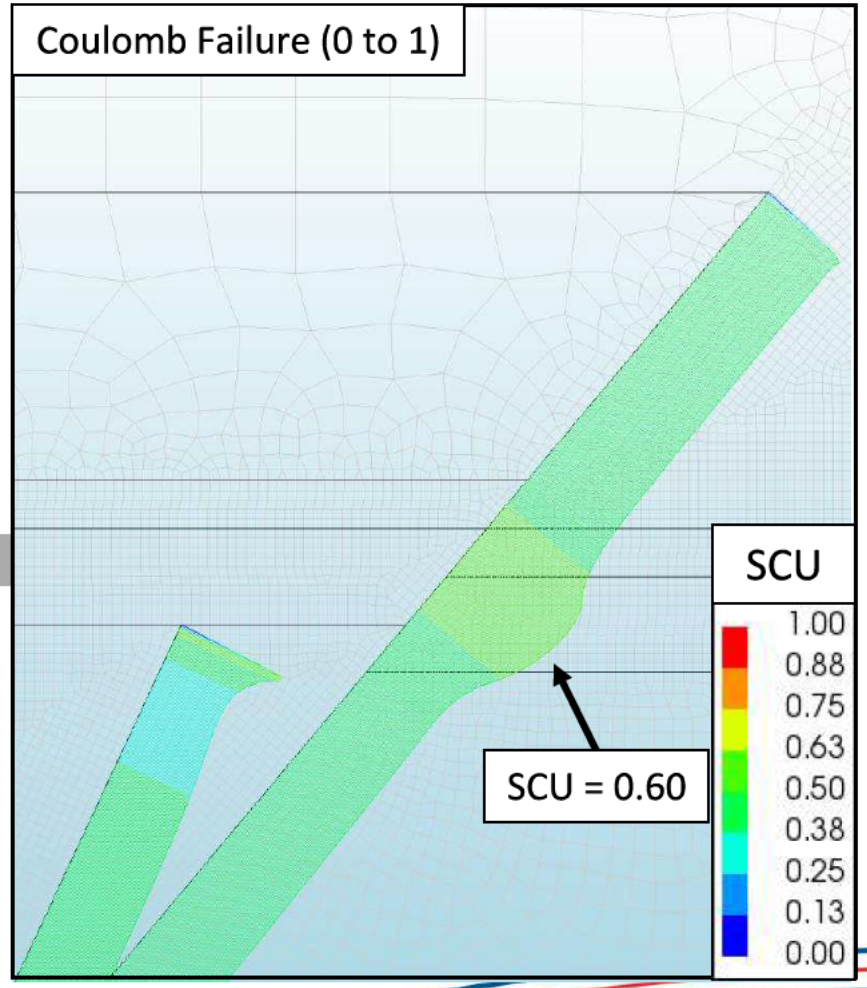
Impermeable fault scenario

Time = 30 years





0.15 millimeter

Faults **remain stable** if there is a large temperature contrast along the fault

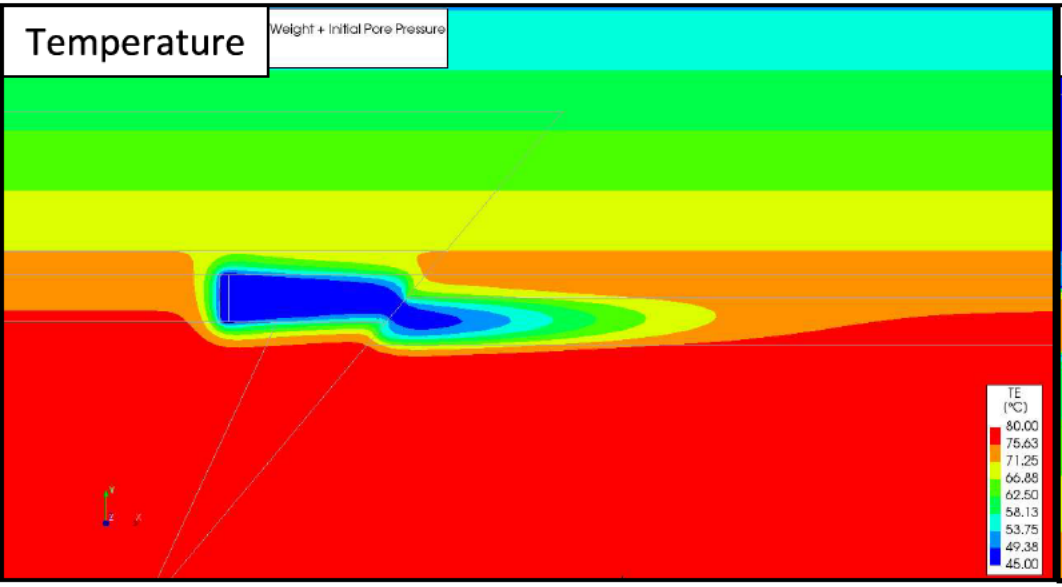
High-skin scenario

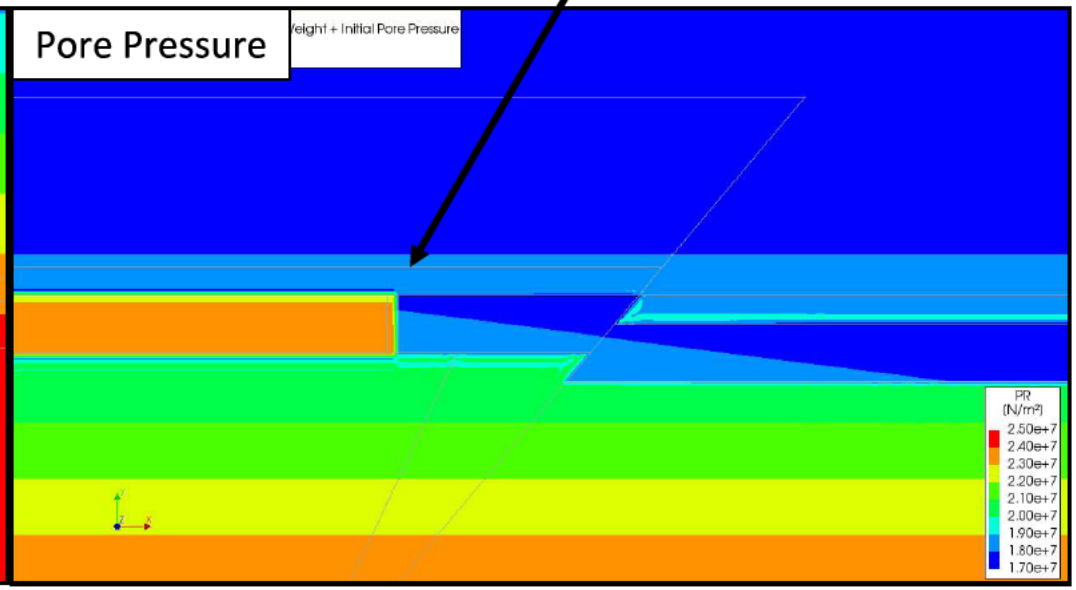
- A high skin would increase the injection pressure locally around the well
- A skin up to **60 bar** is tested, reflecting the maximum allowed injection pressure under SodM criteria
- The pressure impact on the fault is found to be negligible

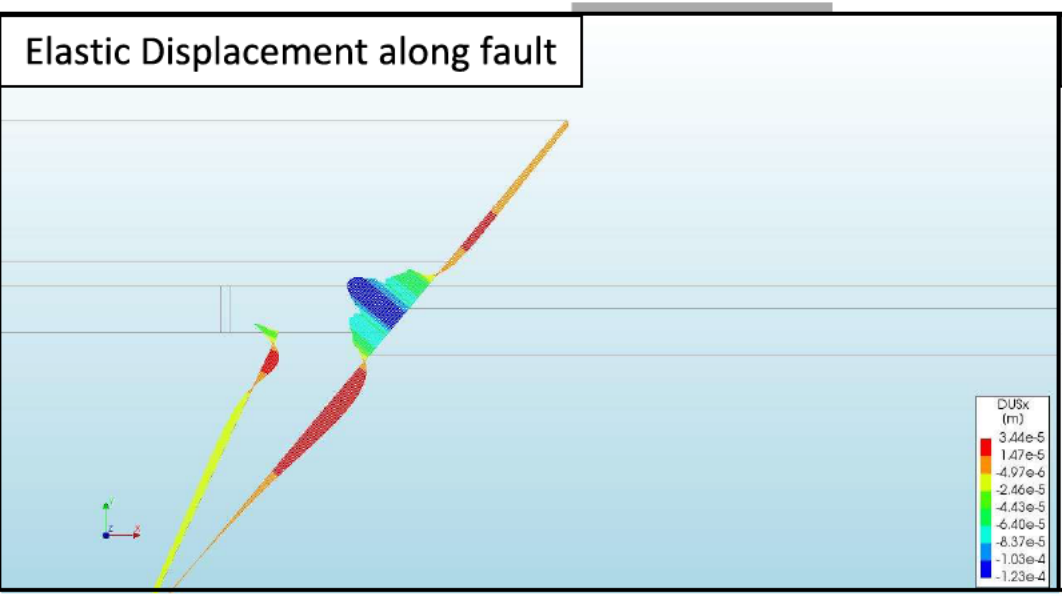
[redacted]

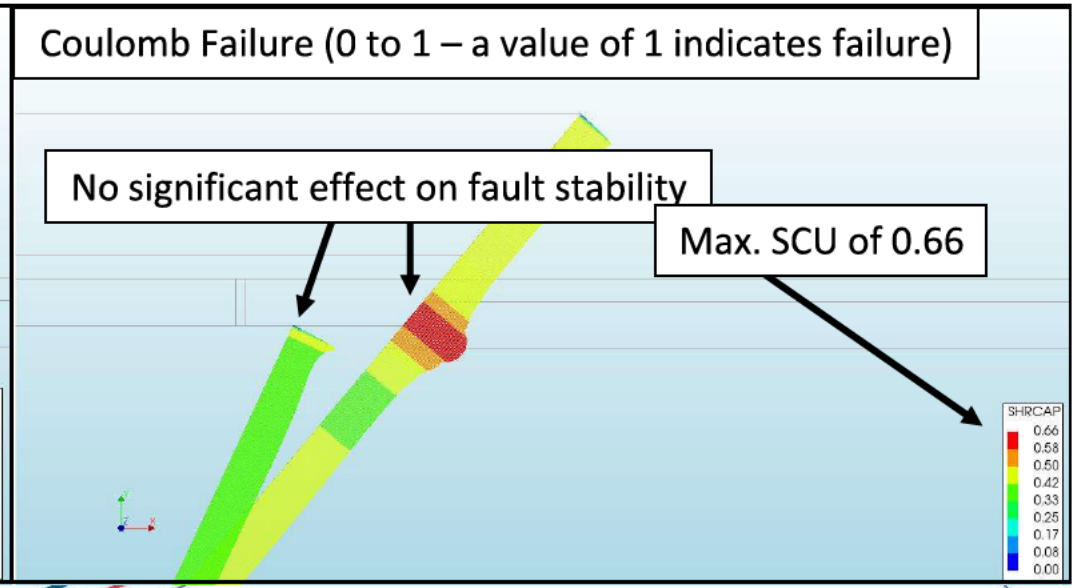
High-skin scenario

High skin (60 bar), high pore pressure around well









Finite Element: Conclusions

- 5 models were shown for HAL
  - Hypothetical depletion

    → **Under similar conditions as Groningen, faults in HAL are far from the failure level (SCU_{max} = 0.60)**
  - Business Case Scenario

    → **Normal geothermal operations have little effect on the stability faults (SCU_{max} = 0.61)**
  - Maximum Business Case Scenario

    → **Maximum injection possible in HAL has increased effect, but remains small (SCU_{max} = 0.71)**
  - Impermeable fault scenario

    → **A completely impermeable fault, resulting in a large temperature contrast, is not expected to produce larger instability (SCU_{max} = 0.71)**
  - High-skin scenario

    → **A high skin will result in a high increase of pressure, and decrease of horizontal stress around the well, but is not expected to affect the faults**

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Probabilistic analysis: Approach A

- The goal of this exercise is to add the possible range of input parameters, e.g. Youngs Modulus, Thermal expansion coefficient, stress gradients.
- Fault parameters are kept **constant**
- Monte Carlo simulation was done on a large range of parameters (1000 runs)
- Triangular distribution is used to omit outliers & this is consistent with DoubletCalc approach

Production parameters: worst case (winter)
Fault parameters: worst case
Reservoir parameters: variable

	Reservoir Temperature (°C)	Thermoelastic coefficient	Injection Pressure (bar)	Vertical stress gradient (bar/m)	Horizontal stress gradient (bar/m)	Fault dip
Minimum	70	0.5	2	0.207	0.158	35
Most likely	73	1	5	0.213	0.165	50
Maximum	76	2	25	0.225	0.172	65

Input parameters

- Reservoir temperature 73 ± 3 °C from measurement
- Combining of **Young's Modulus**, **Poisson's ratio** and **thermal expansion coefficient** these values into a thermoelastic expansion coefficient

$$K_T = \frac{\alpha E}{1-v}$$

- K typically ranges from 0.5 to 2
- Vertical stress gradient determined at 0.207 based on density log, the TNO standard is 0.225. Not expected to be much lower than 0.207
- Horizontal stress gradient determined at 0.165, lowest FIT in the area shows 0.158, maximum set at 0.172
- Fault azimuth was not varied as **worst case** orientation is used (see white dot in slide 22)
- Fault dip is within **most conservative** range

	Reservoir Temperature (°C)	Thermoelastic coefficient	Injection Pressure (bar)	Vertical stress gradient (bar/m)	Horizontal stress gradient (bar/m)	Fault dip
Minimum	70	0.5	2	0.207	0.158	35
Most likely	73	1	5	0.213	0.165	50
Maximum	76	2	25	0.225	0.172	65

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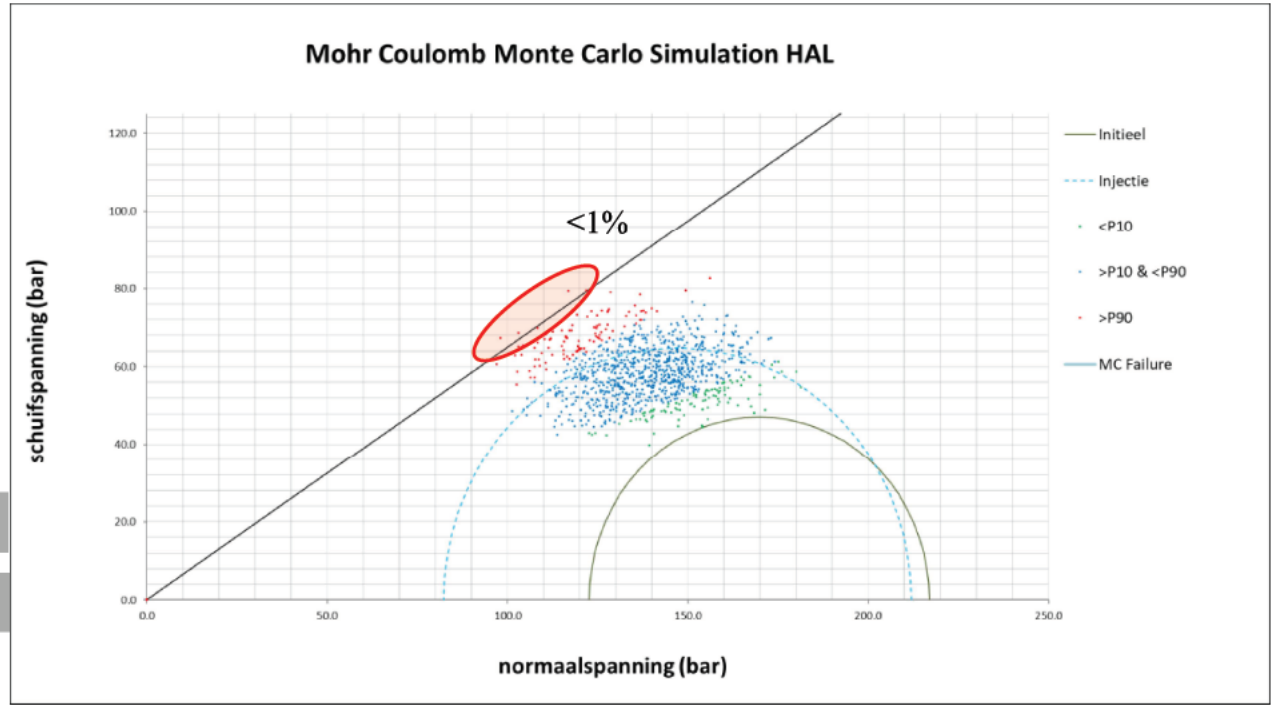
Monte carlo: 1000 runs

Production parameters: worst case (winter)
Fault parameters: worst case
Reservoir parameters: variable

- Only looked at for the **most conservative**
  Mohr Circle ($\sigma_1 - \sigma_3$) (see slide 23)
- **No cohesion** for fault
- **Most critical fault** dips
- Cooling down to **45°C**
- Effect of the 1% cases further investigated in Finite Element Model



For already a worst case, **<1%** of the Monte Carlo simulations fall above the Mohr coulomb failure line

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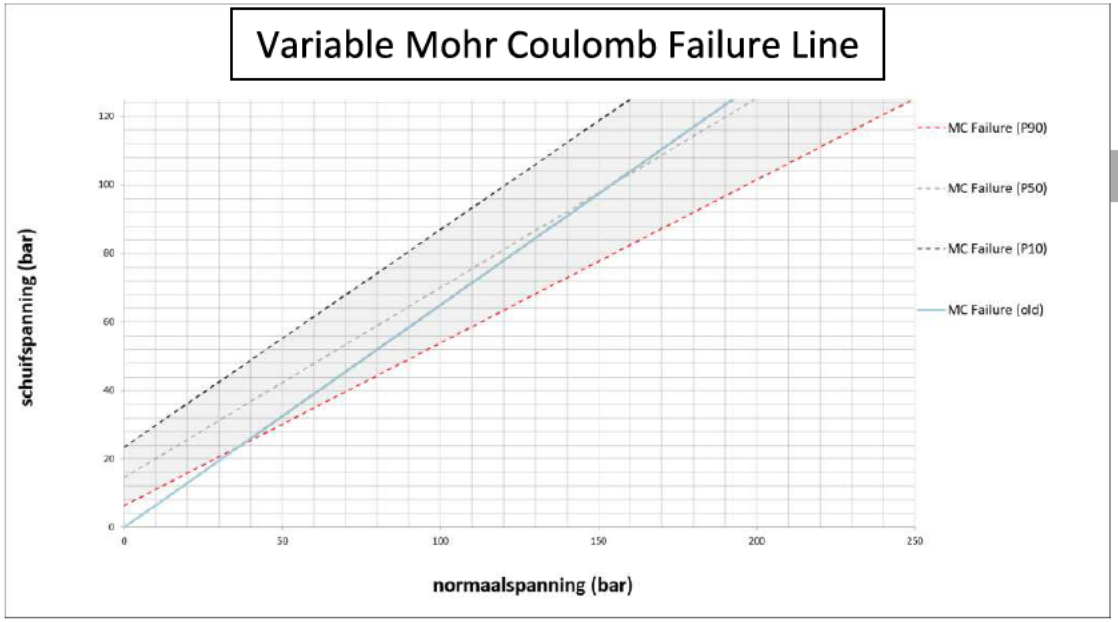
Probabilistic Analyis: Approach B Including fault properties

- An alternative probabilistic scenario also includes the **fault properties**
  - Cohesion: Minimum of 0, maximum of 30 bar. This is a realistic expectation of cohesion from literature.
  - Friction coefficient is an unknown factor, varying from 0.4 to 0.7
  - Dip of fault (already included in approach A



	Fault Properties		
	Cohesion (bar)	Friction coefficient (-)	Dip (degrees)
Minimum	0	0.4	35
Most likely	15	0.55	50
Maximum	30	0.7	65

Production parameters: worst case (winter)
Fault parameters: variable
Reservoir parameters: variable

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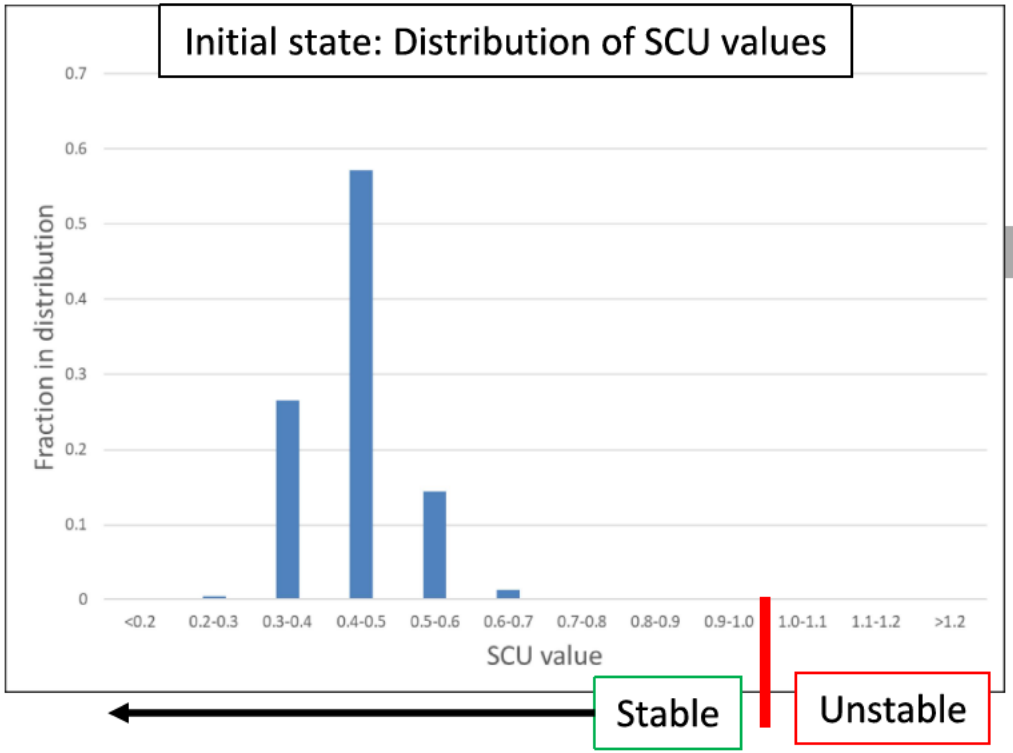
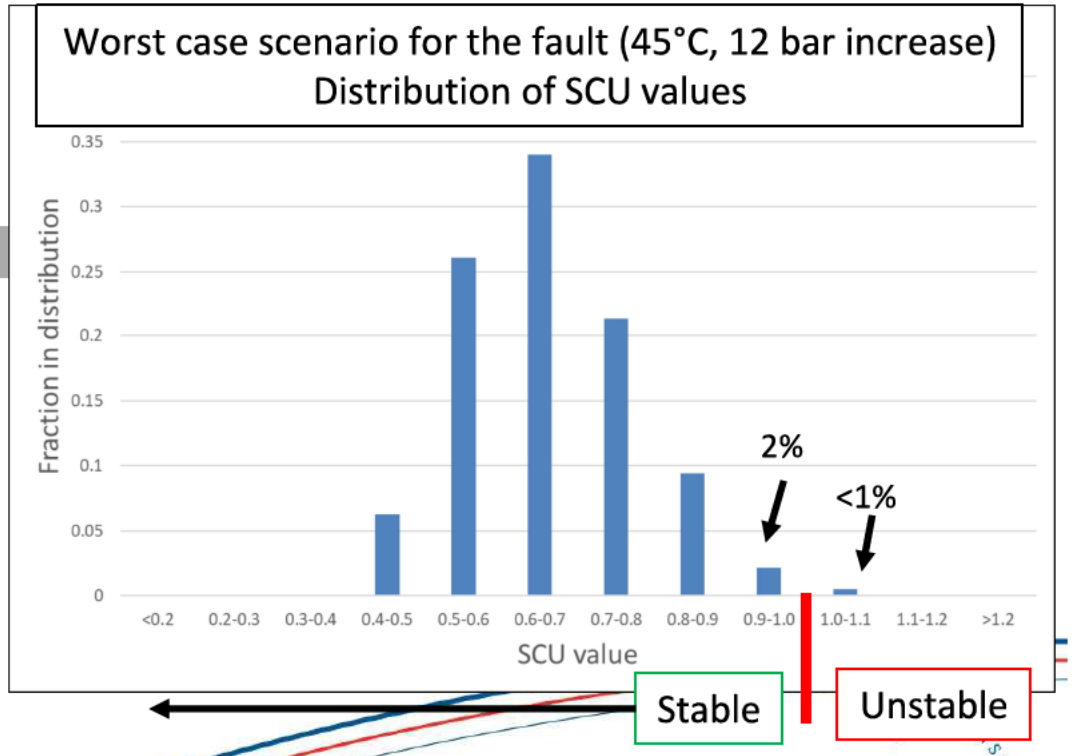
Probabilistic Analyis: Approach B
Including fault properties

- Maximum SCU value of 1.1
- This would result in only **<1%** of the values falling over the failure line
- Bulk of the SCU values are between 0.5 and 0.8, in the stable range





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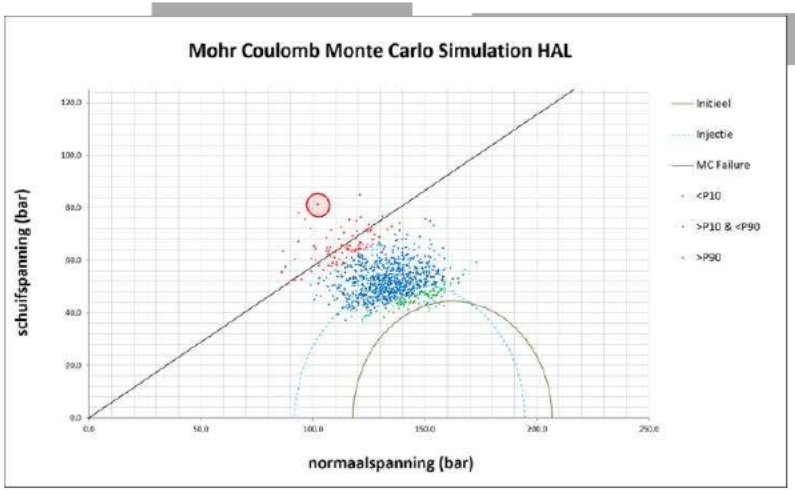
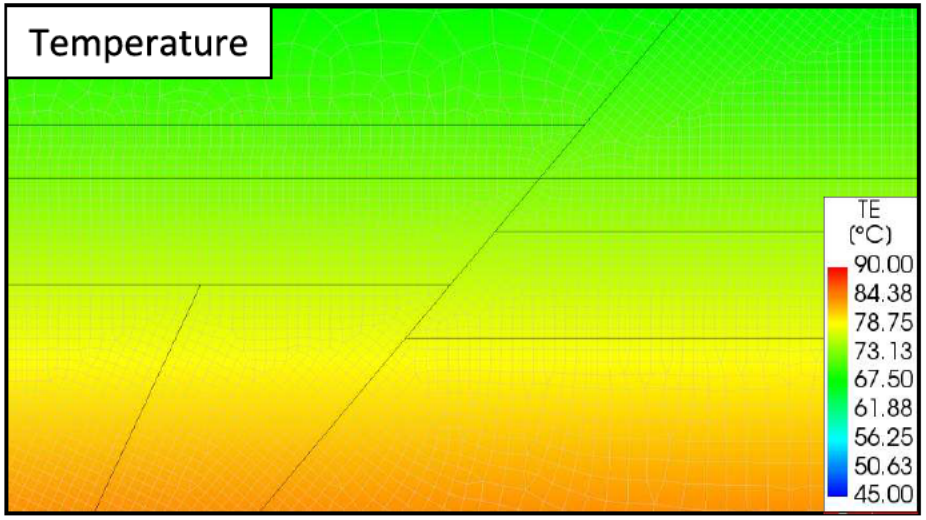
Extreme scenario: What is required to make a fault slip

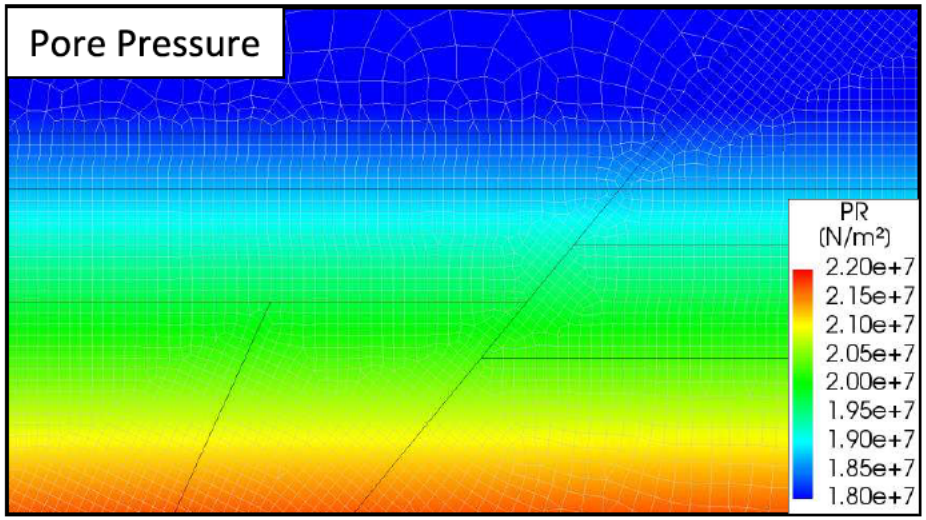
1. The most extreme scenario encountered from the probabilistic analysis (see Appendix 7)
2. Permanent winter conditions, 45°C and 150 m^3/hr injection
3. No cohesion, worst fault orientation

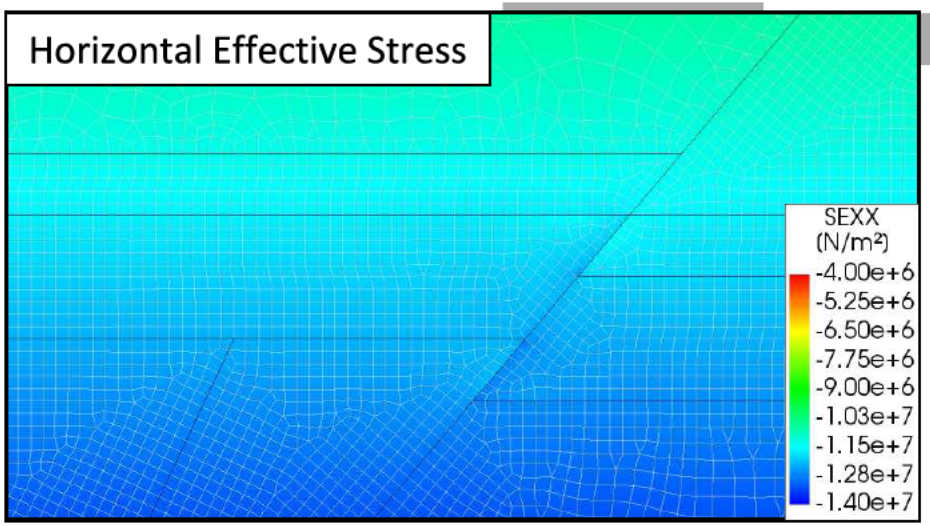


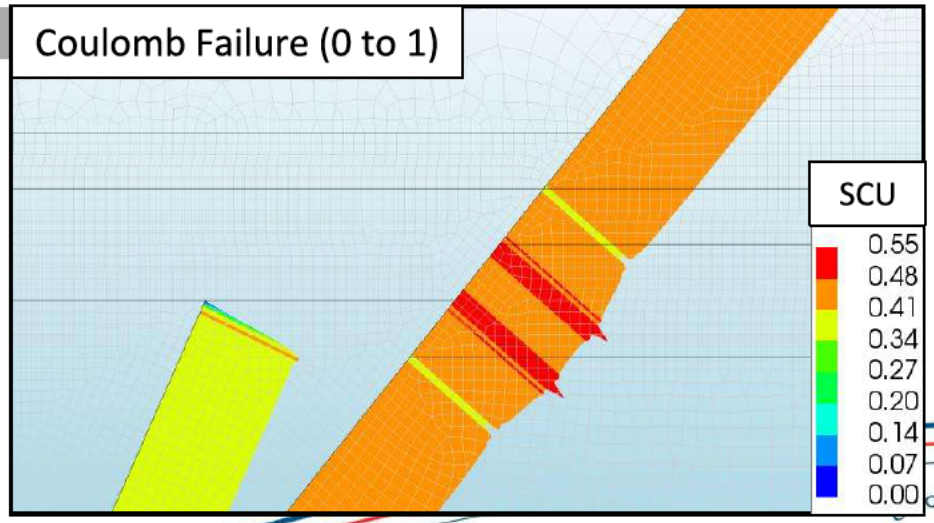
Extreme scenario HAL

Time = 0 years









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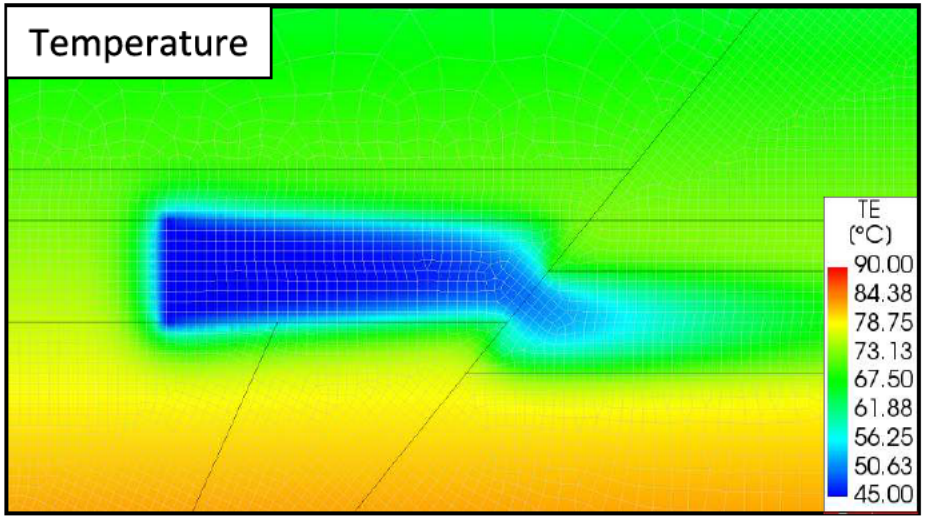
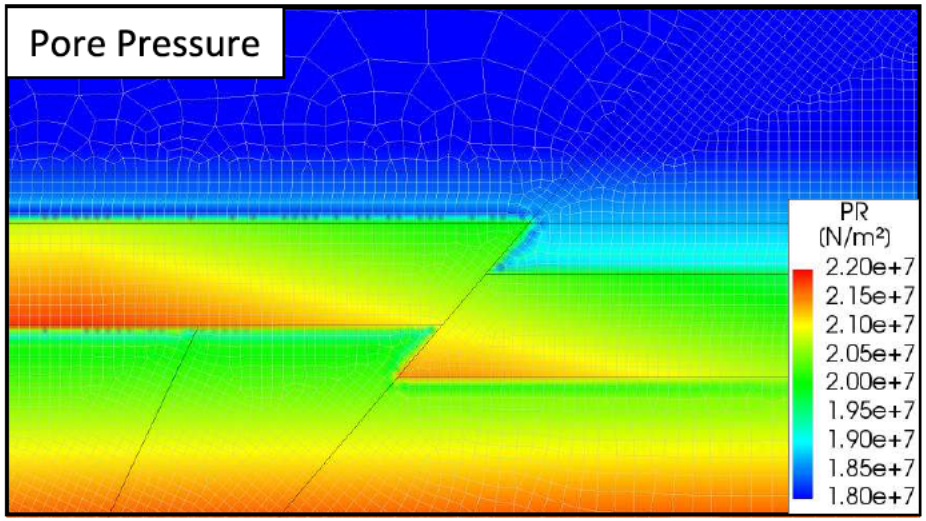
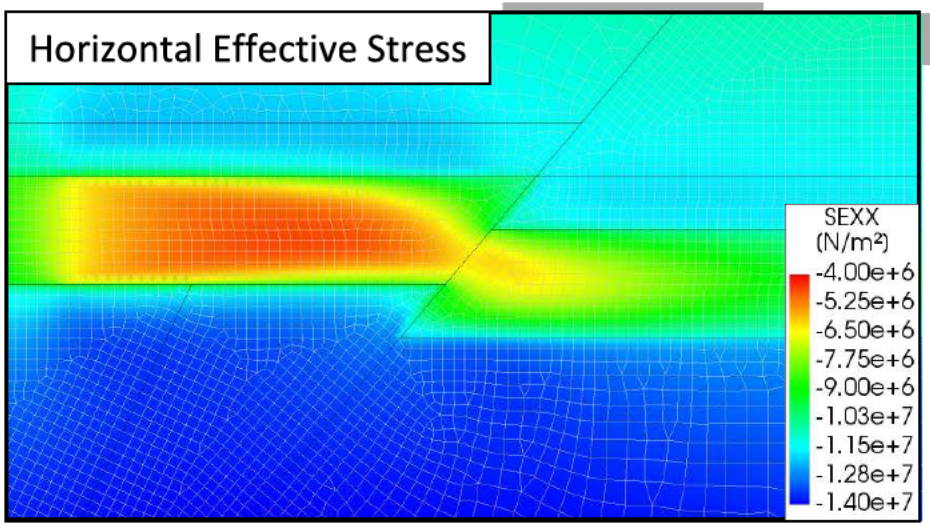
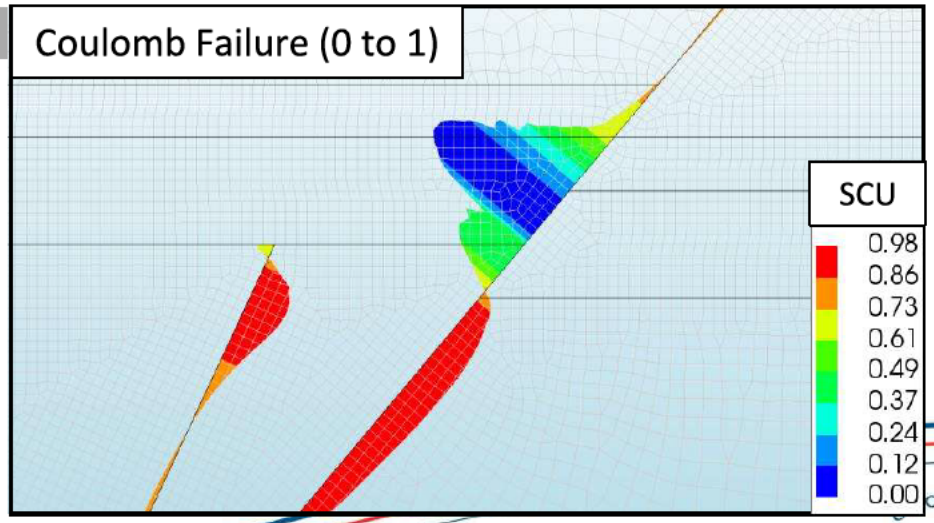
Extreme scenario HAL

Time = 21 years









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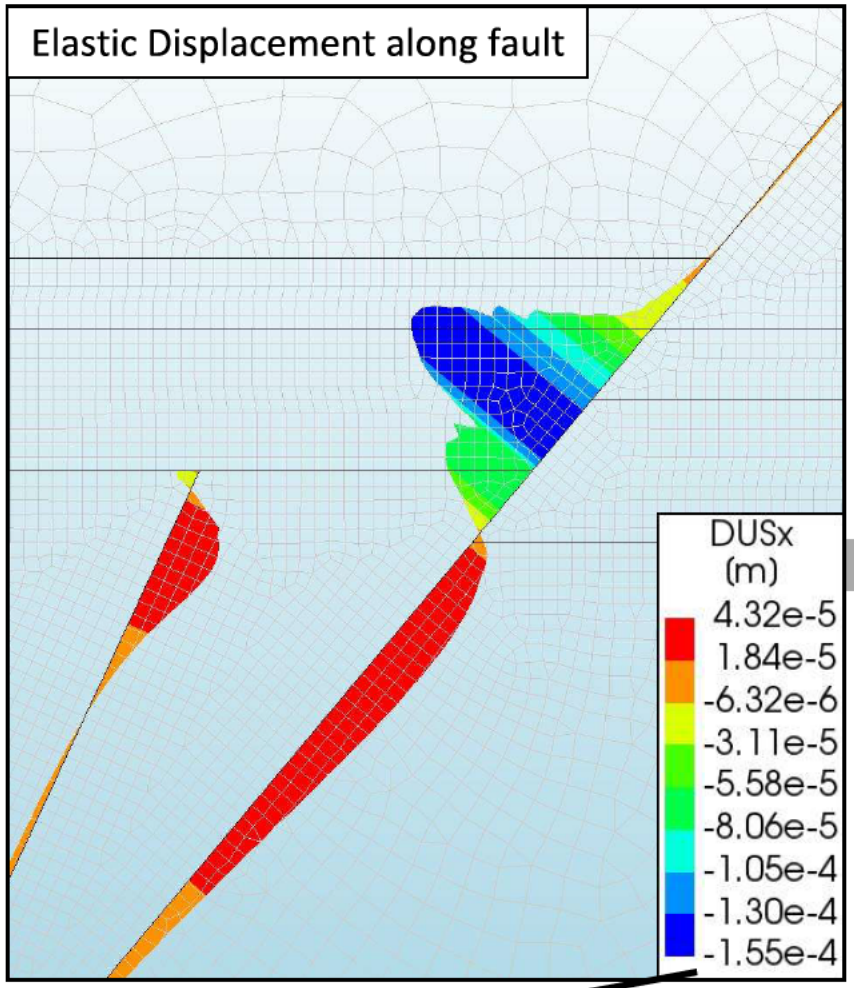
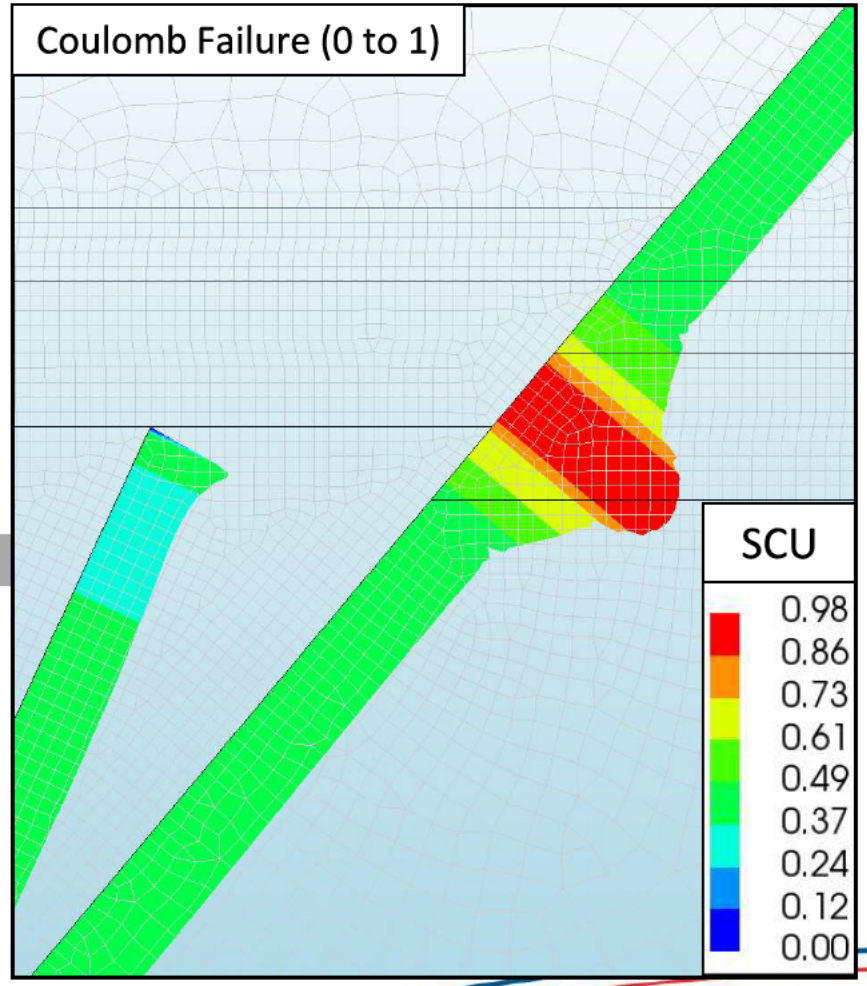
Extreme scenario HAL

Time = 21 years

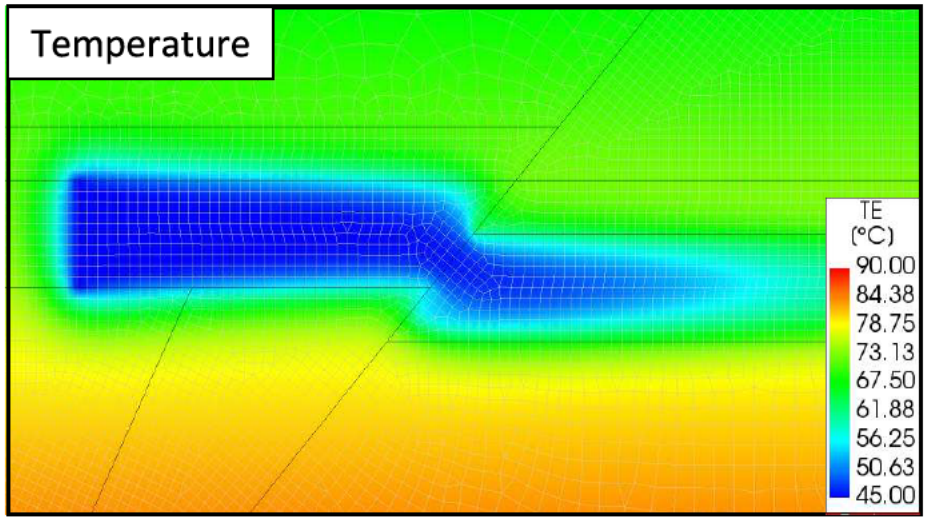


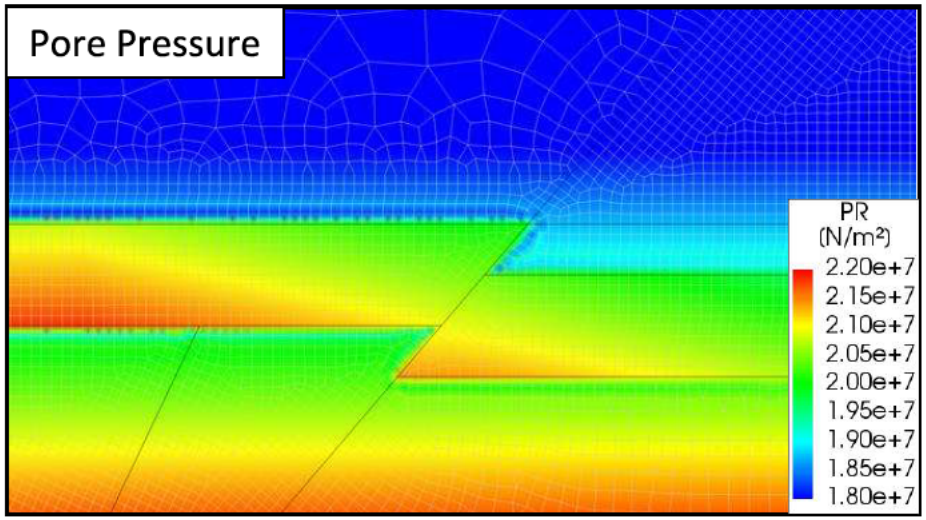


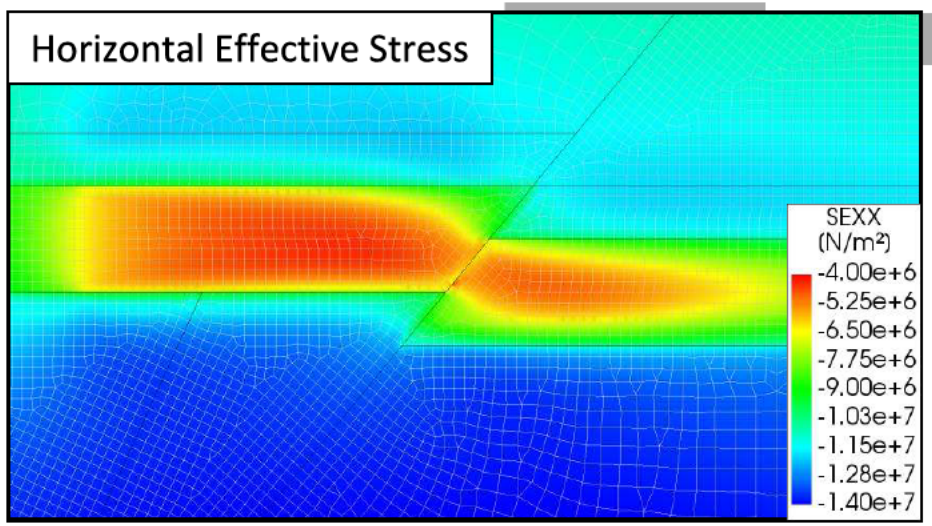
1/10th milimeter

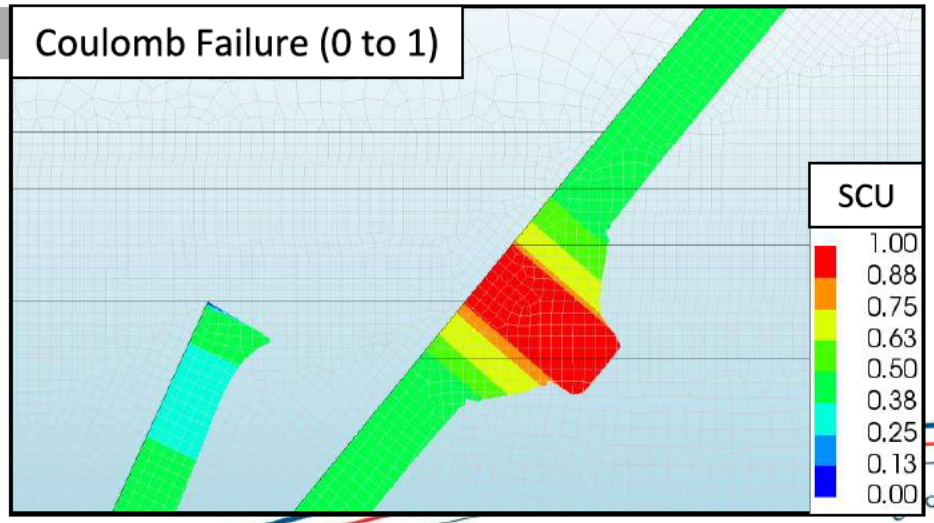
Extreme scenario HAL

Time = 30 years









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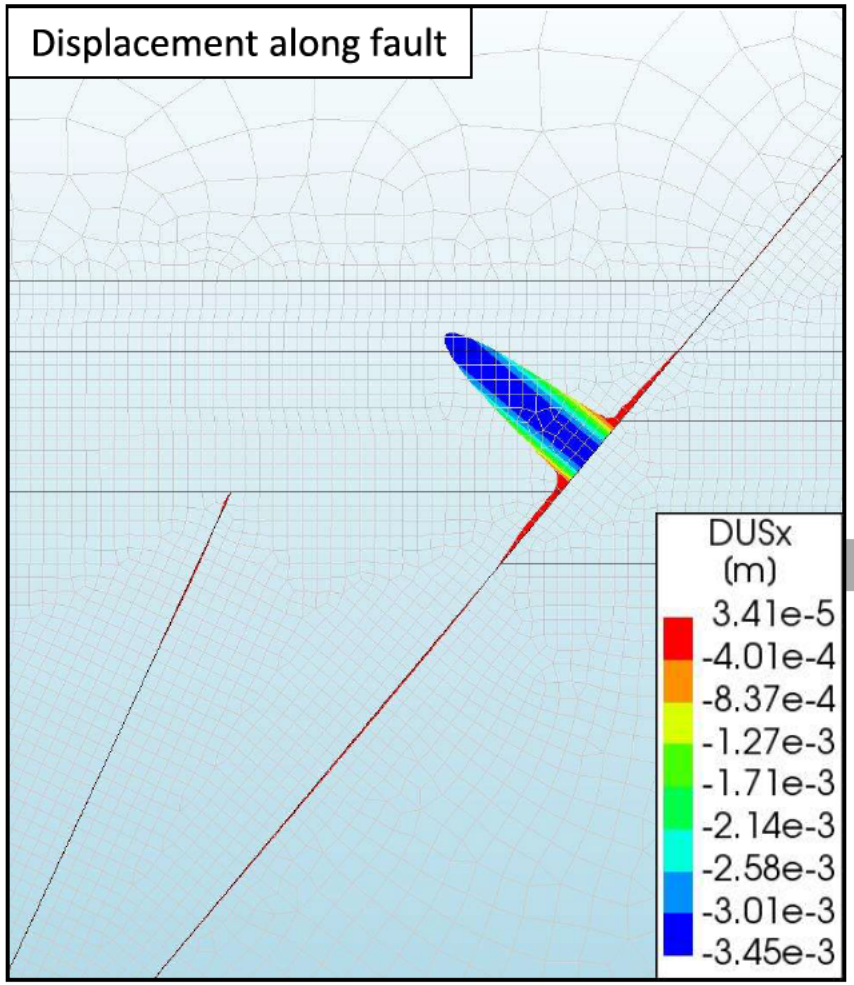
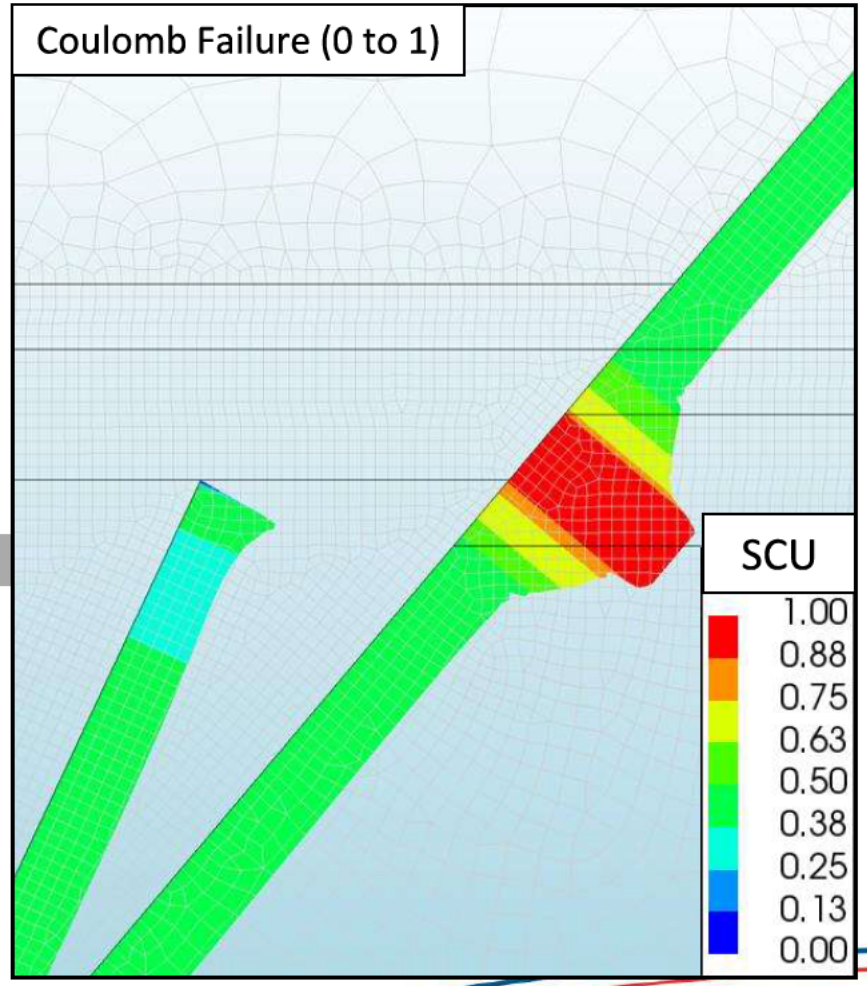
Extreme scenario HAL

Time = 30 years





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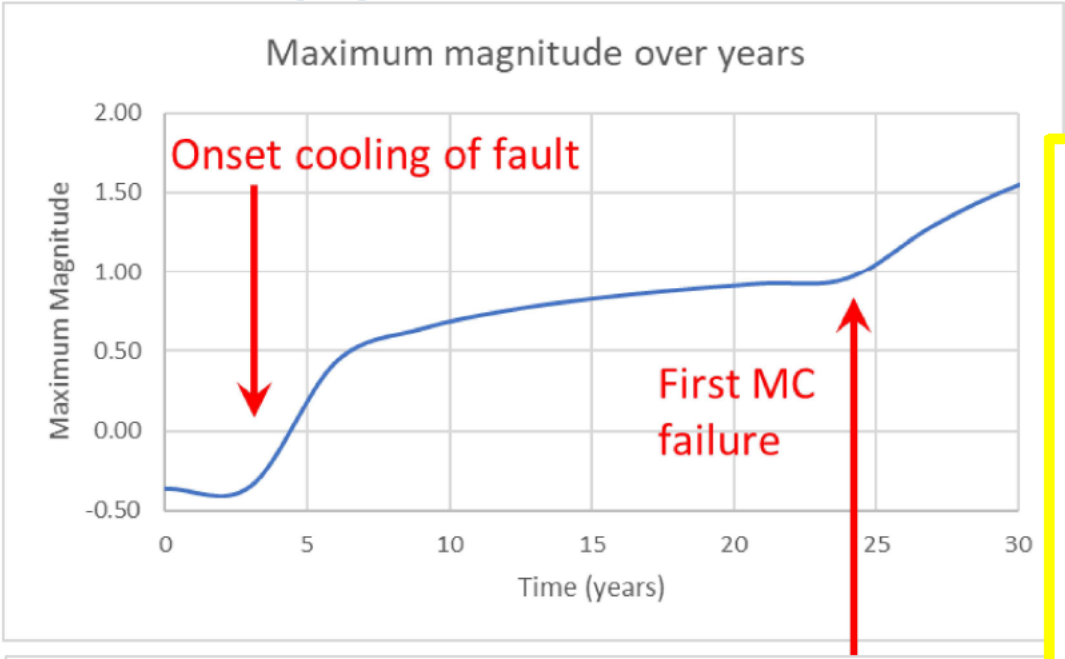
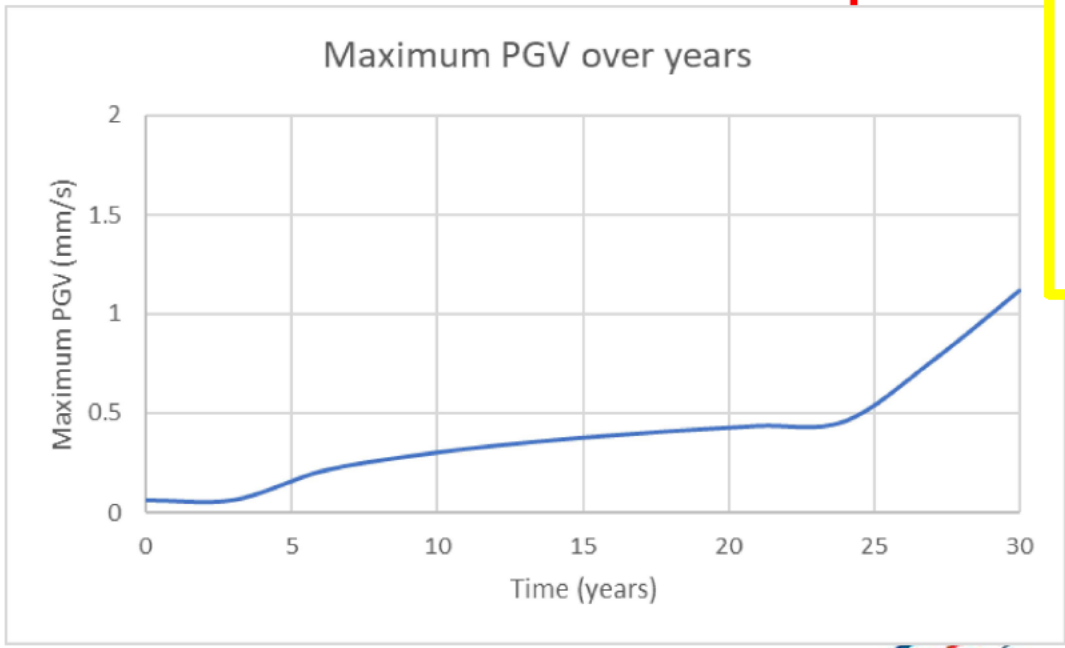
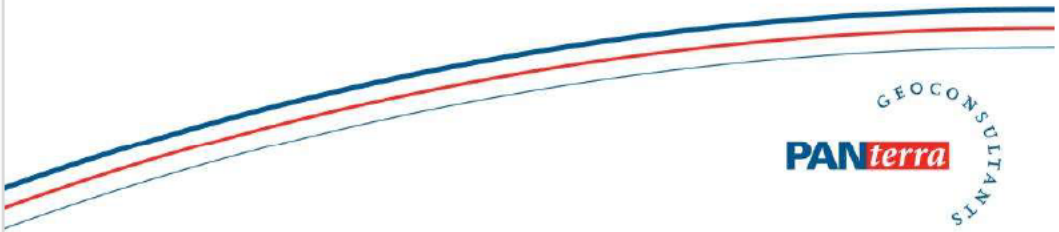
Extreme scenario HAL: Approximate relation to magnitude





Note that this is for:

- An unrealistic parameter set (Appendix 7)
- Completely cooled down fault to 45°C
- No cohesion for the fault
- Conservative fault orientation
- A flow path through the fault
- Maximum offset (50m) of reservoir
- Assuming all release accommodated in 1 event
- Large flow contrast between layers



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Risk matrix

- A qualitative risk matrix was set up according to the IF/QCon guidelines
- Defining the impacts takes into account a trailing effect which may lead to a ~0.5 M_w increase
- Three stages of the project are defined
  1. Prior to production, there is no induced seismicity expected
  2. During production, it is very unlikely an *average* impact ($M_w > 1.5$) will happen
  3. Setting up a TLS qualitatively lowers the impact to *minimal*

Possibility of induced seismicity	Impact				
	Negligible $M_w < 1.0$	Minimal $M_w > 1.0$	Average $M_w < 1.5$	Significant $M_w > 2.5$	Severe $M_w > 3.5$
Very likely					
Likely					
Possible					
Unlikely					
Very unlikely	1	3	2		

Traffic Light System (TLS)

- To mitigate the possible impact in terms of surface effects a TLS was set up
  - Based on the geomechanical results this is defined in the risk matrix as a **very unlikely** scenario
- The Traffic Light System is to be monitored by 3 seismic monitoring stations
- It is proposed on the basis of localized seismicity to the HAL project
- Threshold values of the TLS are to be verified and/or updated after seismic monitoring stations are installed to accommodate for background readings, sensitivity and technical capability of the stations

Traffic Light System (TLS)

- A PGV value of **1 mm/s** is considered a threshold which is noticeable on the surface. With use of the GMPE relations of Groningen this rougly corresponds to a M_w of 1.3. Both these values are used for the green part of the TLS, which means operations may continue as normal as long as measurements remain under these values.
- Values between 1 and 1.6 mm/s (PGV) and 1.3 and 1.6 (M_w) is considered a yellow part of the TLS. This is possibly noticeable on the surface, but not expected to cause any damage. Action however should be taken (a 50% temporary reduction of production is suggested), and models should be evaluated with production history to propose an adjustment of the plan. The aim should be to get back to the green part of the TLS.
- A PGV value of 1.6 mm/s is here considered a threshold to be noticed on the surface. This roughly corresponds to a M_w of 1.6. This is considered a stop threshold for the operation and needs to be thoroughly investigated, including possible mitigation measures.

Traffic Light System (TLS)

	PGV (mm/s)	M_w	Mitigation
Stop	> 1.6	> 1.6	- Report to regulator - Continue seismic monitoring - Bring production to a halt - Evaluate geomechanical models and history match with observed event(s). Investigate mitigation measures. - Propose new production plan
Evaluate	> 1.0 < 1.6	> 1.3 < 1.6	- Report to regulator - Continue seismic monitoring - Lower injection pressure to 50% temporarily - Evaluate geomechanical models and history match with observed event(s) - Propose new production plan
Continue	< 1.0	< 1.3	- Continue seismic monitoring - Continue production as planned - Update geomechanical models and outcomes with periodic injectivity measurements - Update production plan when necessary

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Other possible mitigation measures

1. Increase injection Temperature
   - This will ‘heat up’ a critical fault and is shown to restabilize the fault
   - Dependent on production history; propagation of flow is restricted by time

2. Decrease injection rate
   - Injection rate is of relatively less impact than temperature effect
   - Decrease/stop of injection would give the system time to heat up

Conclusions

1. Mohr Coulomb analysis shows that production will **not** bring the situation to a critical state for **worst case** fault and production parameters and conservative reservoir parameters
2. Calibrated Finite Element Model shows **far from** critical failure for HAL in multiple production scenarios under **worst case** fault and conservative reservoir parameters
3. Under Groningen depletion conditions, faults in HAL would **remain stable**
4. There is a **very low** possibility that an unmapped fault reaches a critical state under **worst case** fault and production parameters
5. Extreme scenario is extrapolated to a possible magnitude in the order of Mw = 1.6 after **30 years**.
   - This is considered very unlikely (<0.1% chance)
   - Can be mitigated by decreasing pressure or increasing injection temperature

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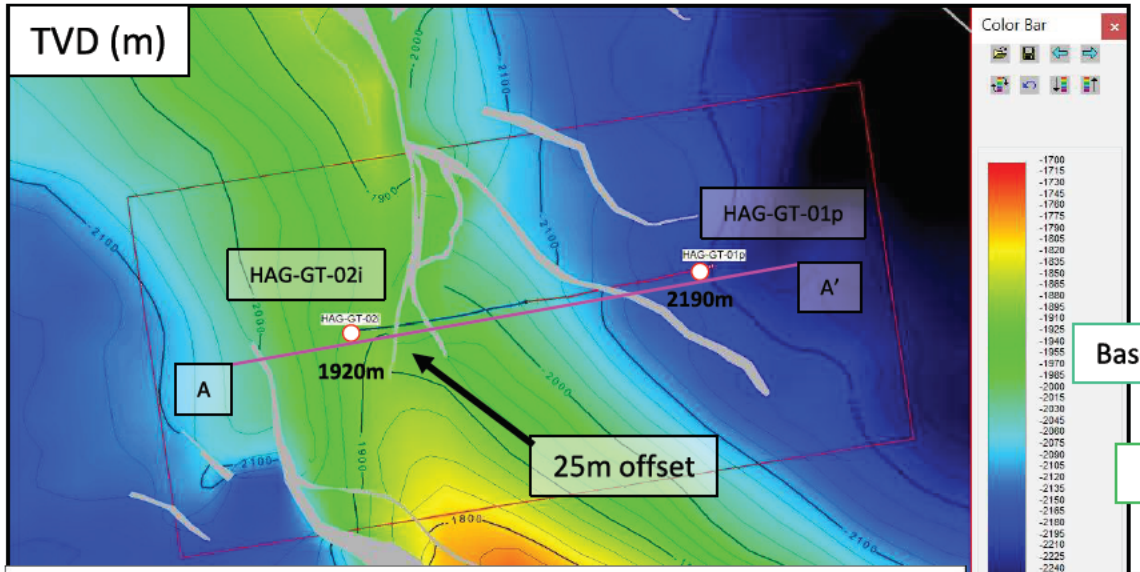
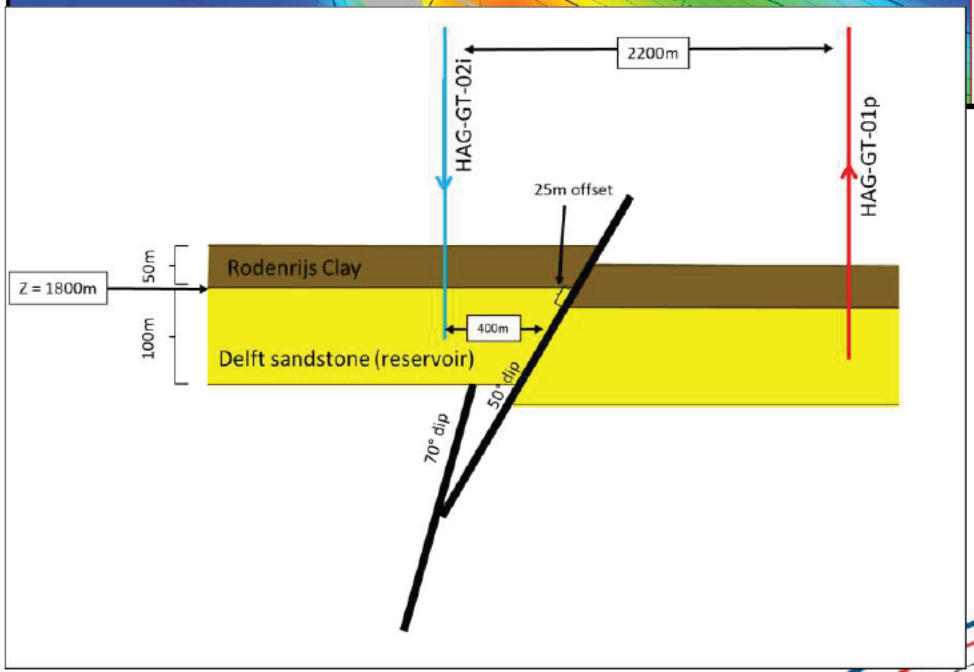
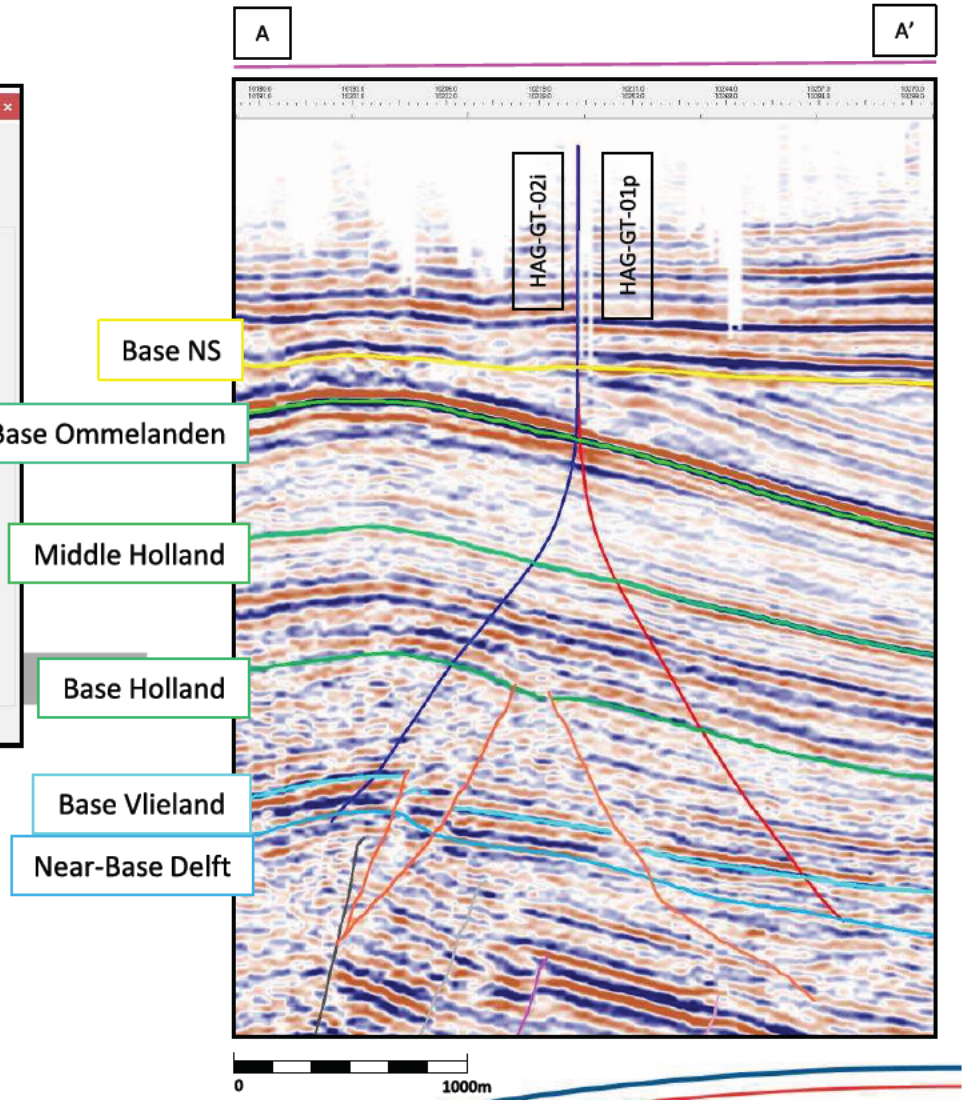
Appendix 1: Geology: Structure and connectivity

Geological Setting HAL

Near Base Delft map







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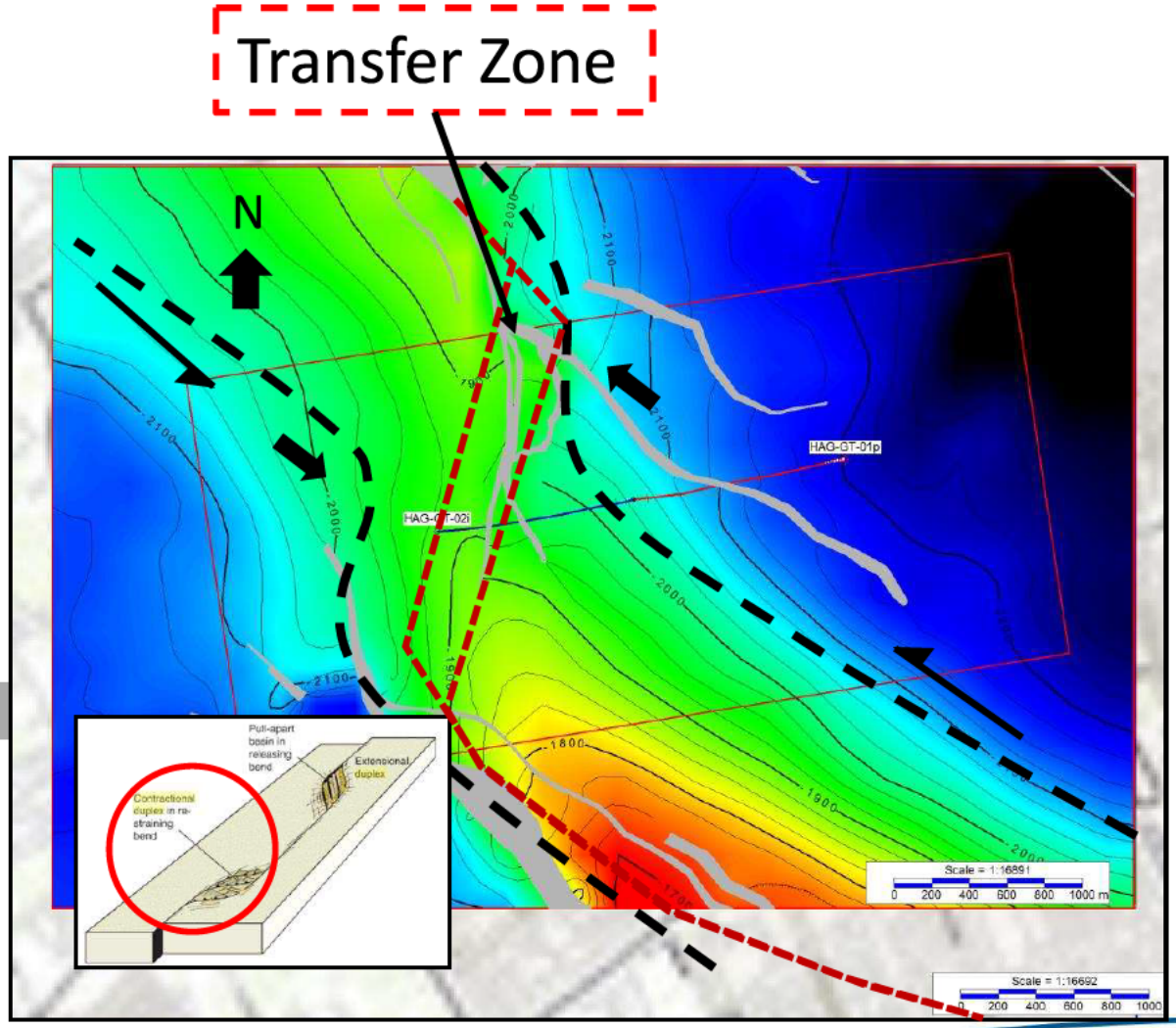
3) Structural Interpretation

The injector HAG-GT-02i is drilled in a major (inactive) fault zone, in a compressional bend.

The well is positioned in the transfer zone. This results in a denser fault network around this well.



Near-Base Delft depth map

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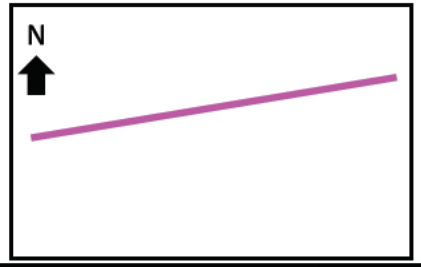
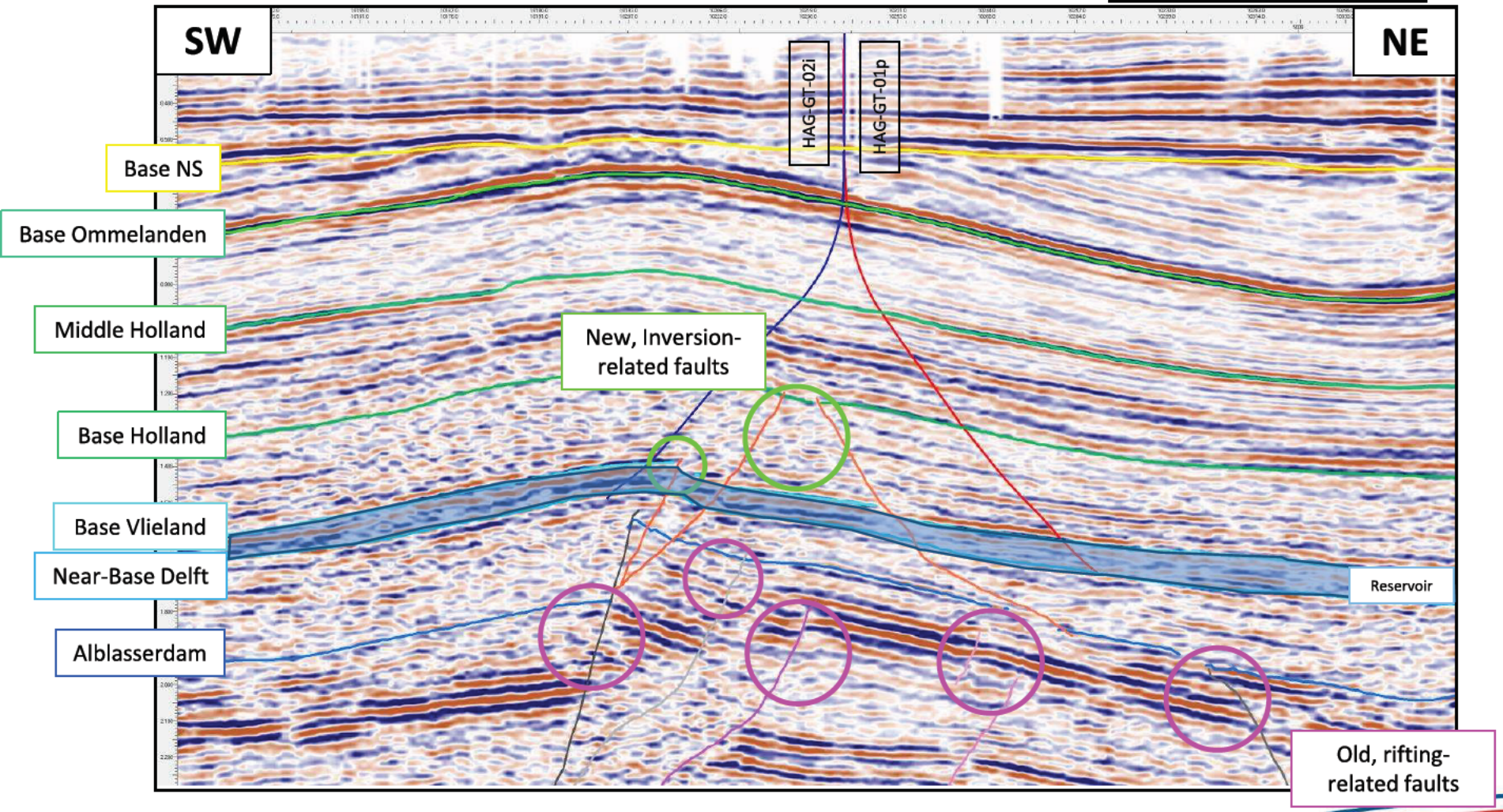
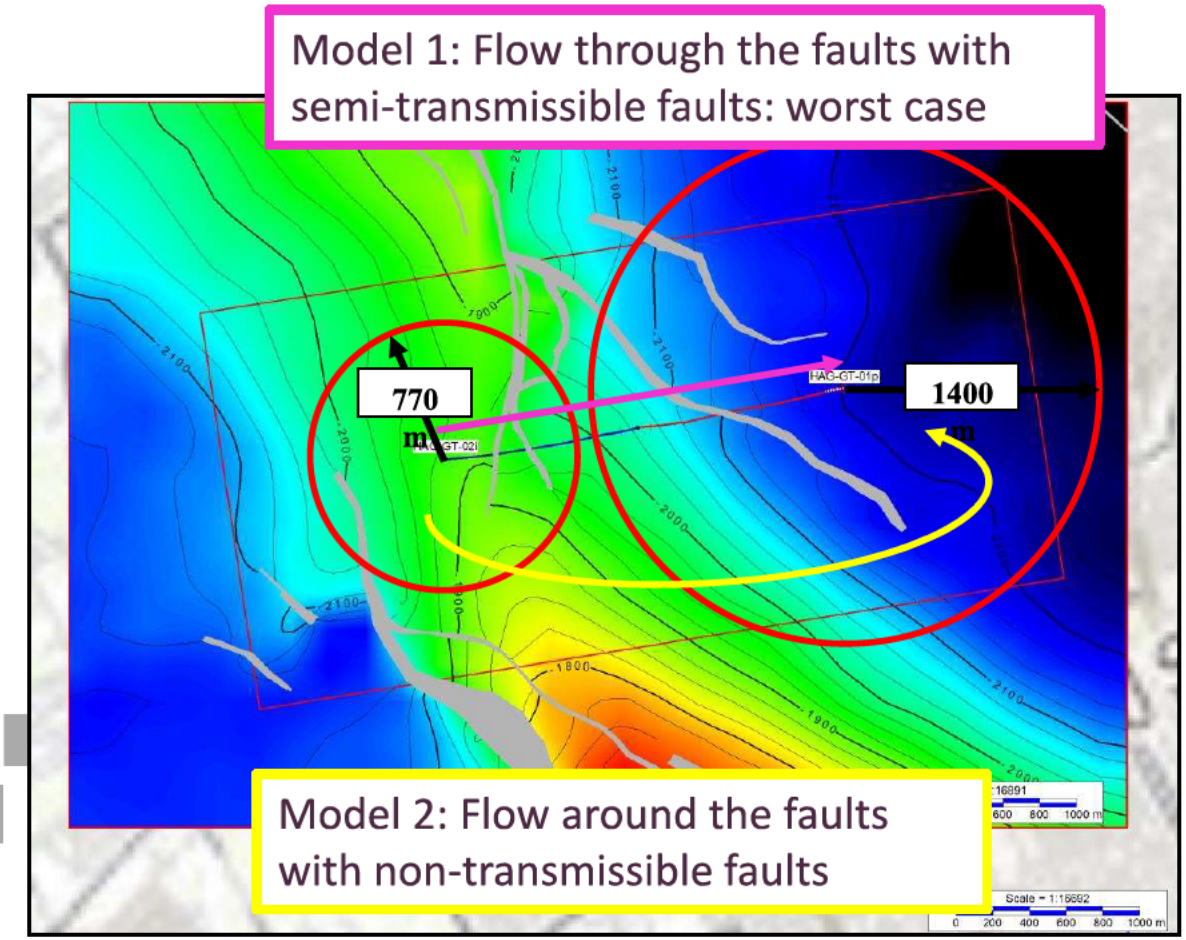
2) Faults


N


SW
NE
HAG-GT-02i
HAG-GT-01p
Base NS
Base Ommelanden
Middle Holland
Base Holland
Base Vlieland
Near-Base Delft
Alblasserdam
New, Inversion-related faults
Reservoir
Old, rifting-related faults

Connectivity HAL

- HAG-GT-02i well test: 1400 mD
  - Baffle at 770m
- HAG-GT-01p well test: 2300 mD
  - Baffle at 1400m
- Interference test: Minimum of 280 mD, higher permeability models (366 and 686 mD also match the data)
- Baffles were not linked to faults
- Less high permeability of interference test is most likely caused by a lower fault permeability and/or offset along the fault reducing connectivity
- Geologically 2 flow models possible: The worst case **(Model 1)** is used



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Appendix 2: Stress Field derivation

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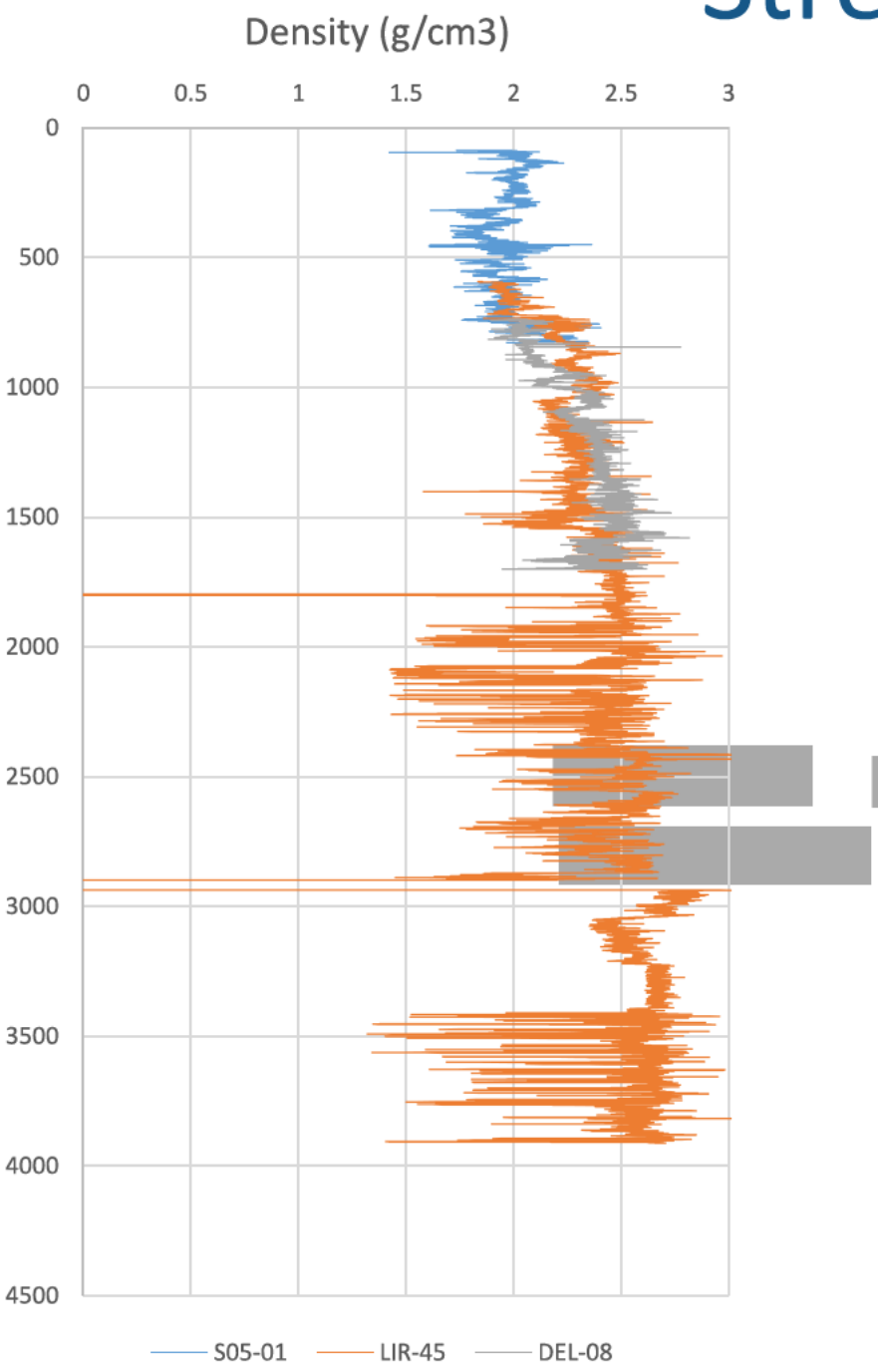
Stress field (1)



- Density profile from West-Netherlands basin from density logs of well LIR-45
- Top section from offset density log of S05-01 up to 40m.
- Density log is corrected for wash-outs and top section (See Appendix 3)
- DEL-08 is shown for comparison to HAL area
- The resulting vertical stress gradient for HAL is **0.207 bar/m**

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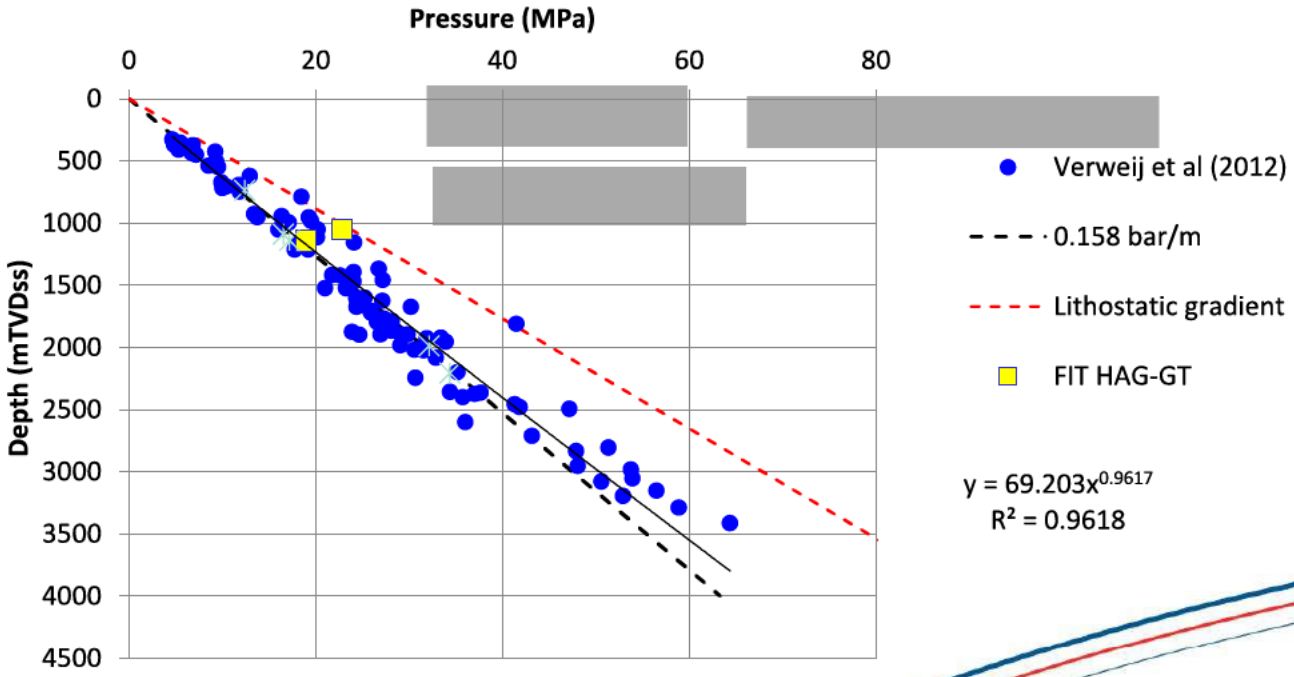
Stress field (2)

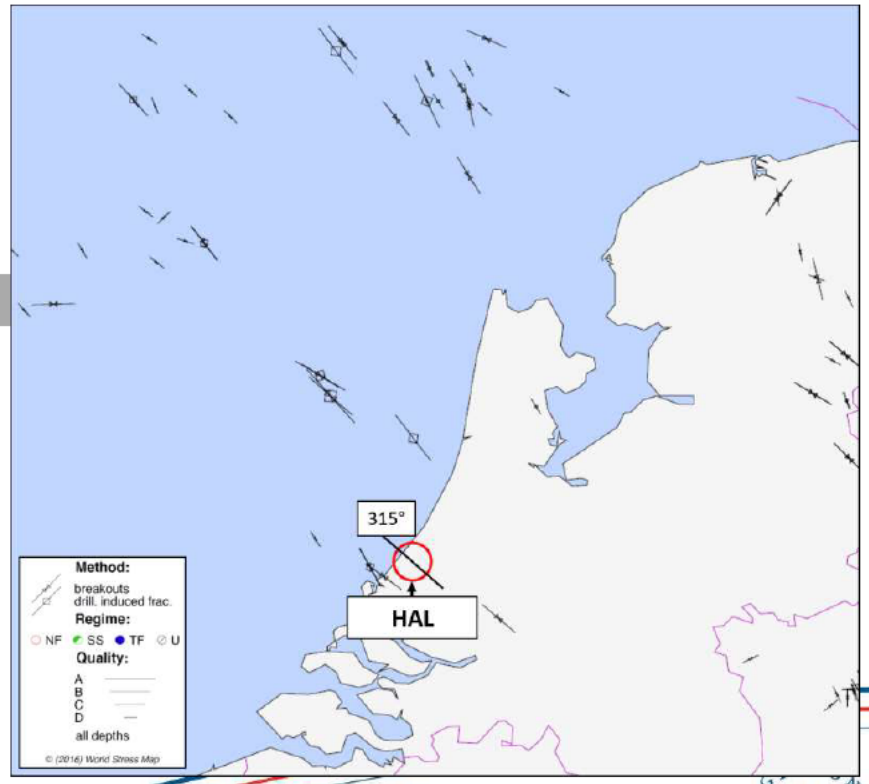
- Minimum horizontal stress gradient can be derived from offset Leak Off Tests (Verweij et al., 2012)
- Formation Integrity Test from HAG-GT-01p indicates a potential higher minimum stress gradient
- The resulting minimum horizontal stress gradient is **0.165 bar/m**



Stress field (3)

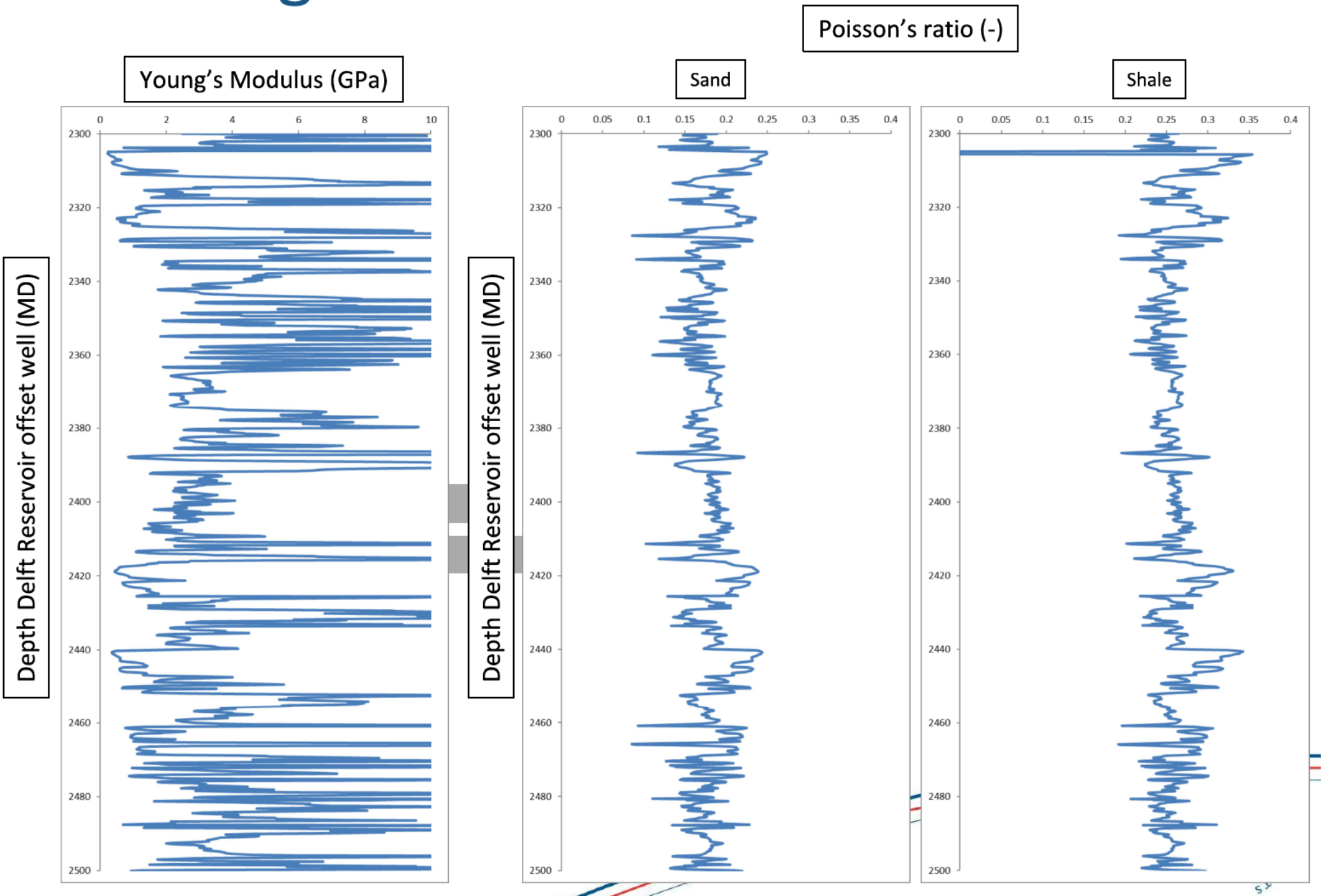
- The maximum horizontal stress is not determined in the West-Netherlands Basin
- There is a clear orientation of the maximum horizontal stress field trending approximately 135°/315°
- A core-based relation from Groningen is used

  $S_H = 1.32 \cdot S_h - 0.32 \cdot P_p$ (Mechelse, 2017)
- This results in a maximum horizontal stress gradient of **0.184 bar/m**

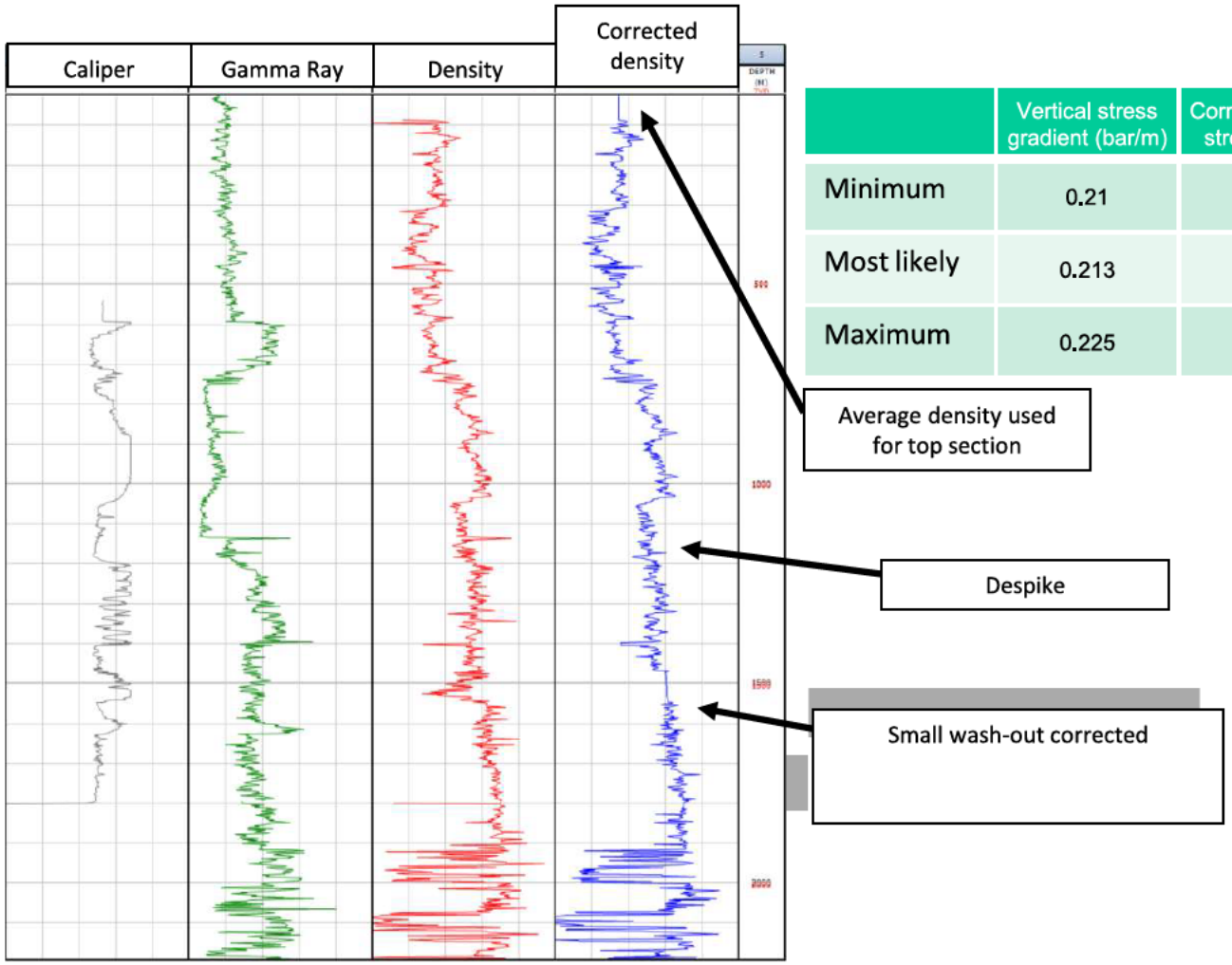


Appendix 3: Reservoir parameters from logs

Young's modulus & Poisson's ratio



Density log correction



	Vertical stress gradient (bar/m)	Corrected vertical stress gradient	Explanation
Minimum	0.21	**0.207**	Minimum top-section density
Most likely	0.213	**0.214**	Average top-section density
Maximum	0.225	**0.225**	Standard value The Netherlands (TNO, multiple occasions)

Appendix 4: Ground motion prediction

[redacted]

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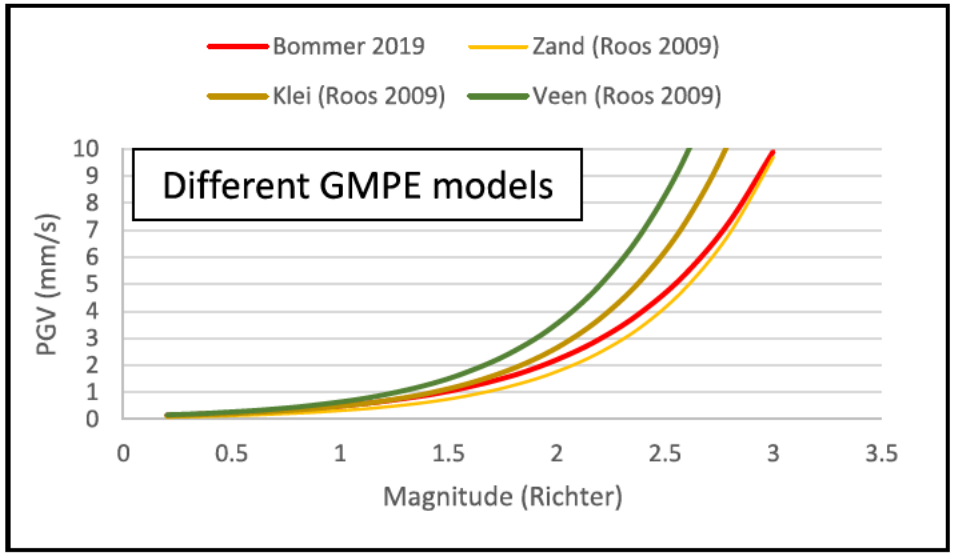
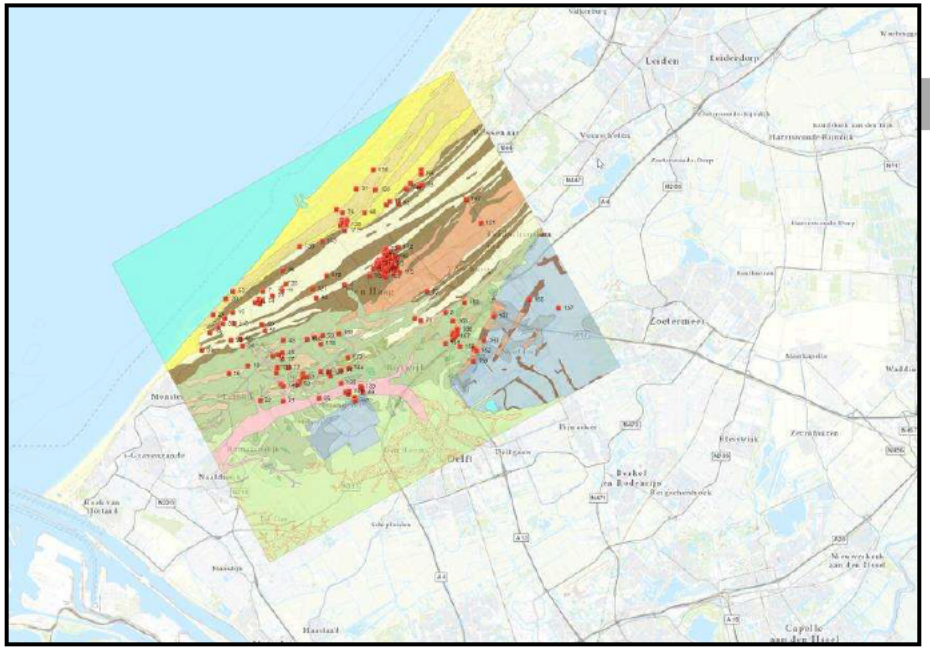
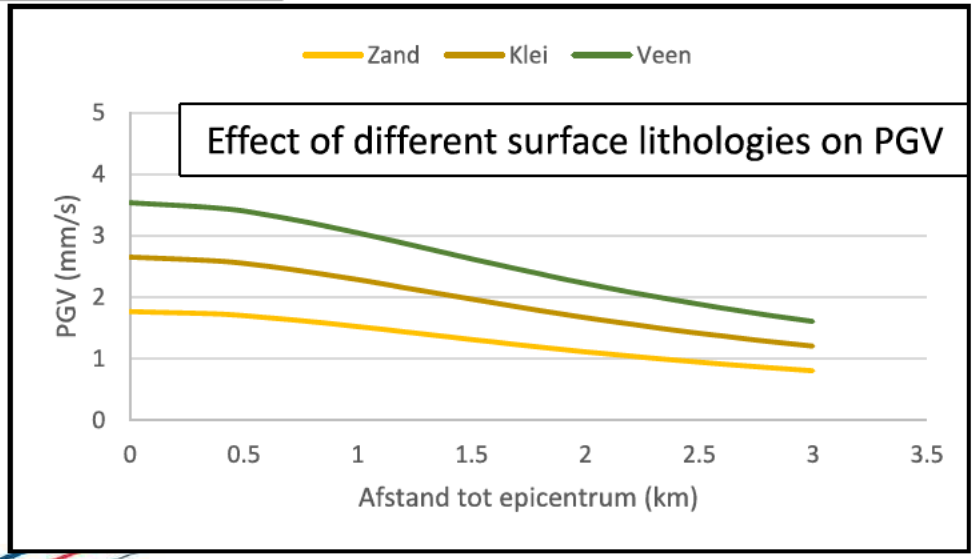
Ground Motion Prediction: extreme scenario HAL

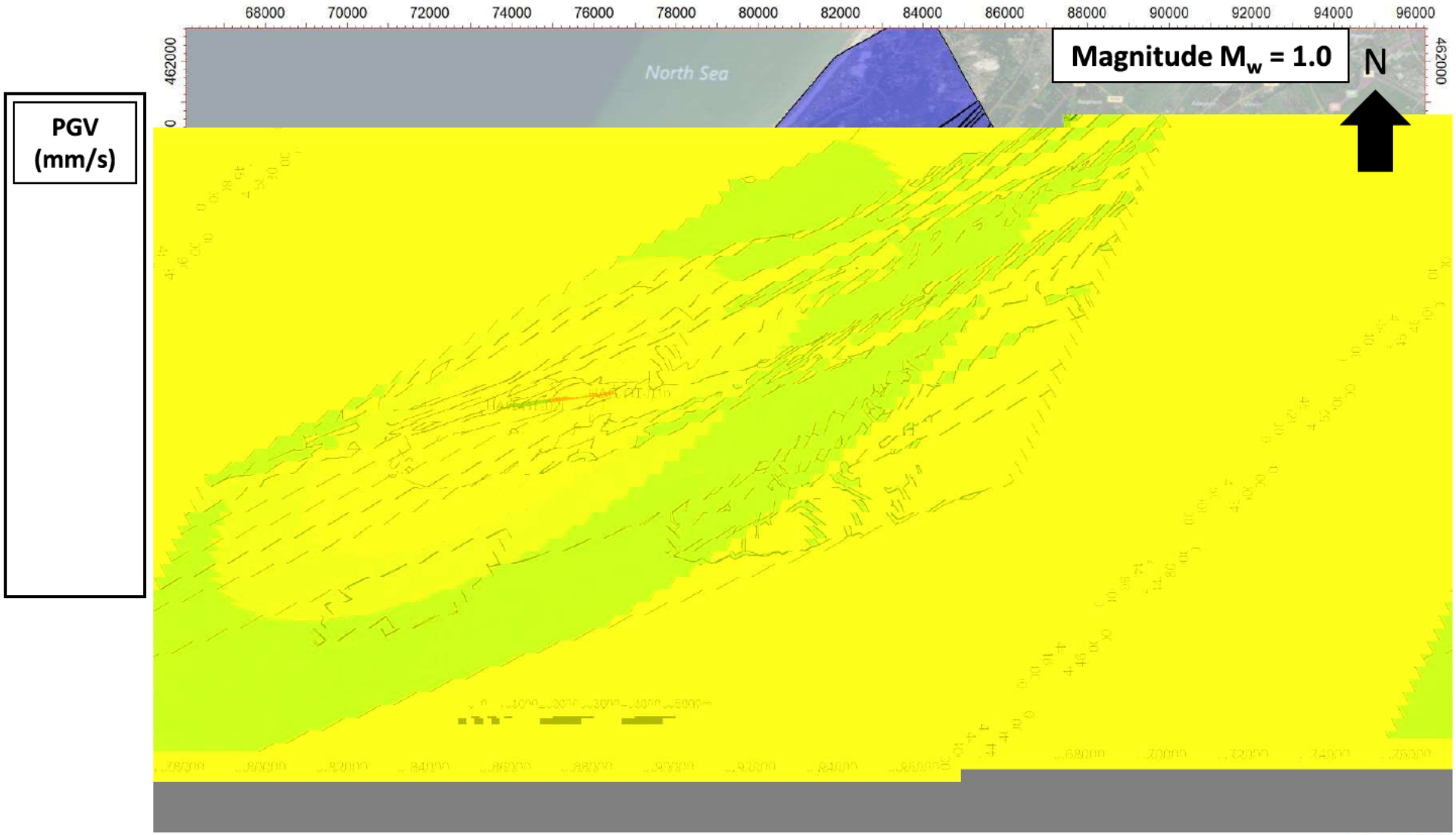
- To create Peak Ground Velocity maps, the GMPE relation by Roos (2009) was used
- The type of surface has a significant effect on the predicted PGV
- The PGV is about 2 times smaller at a 3km (surface) distance from the epicentre







Ground Motion prediction $M_w = 1.0$



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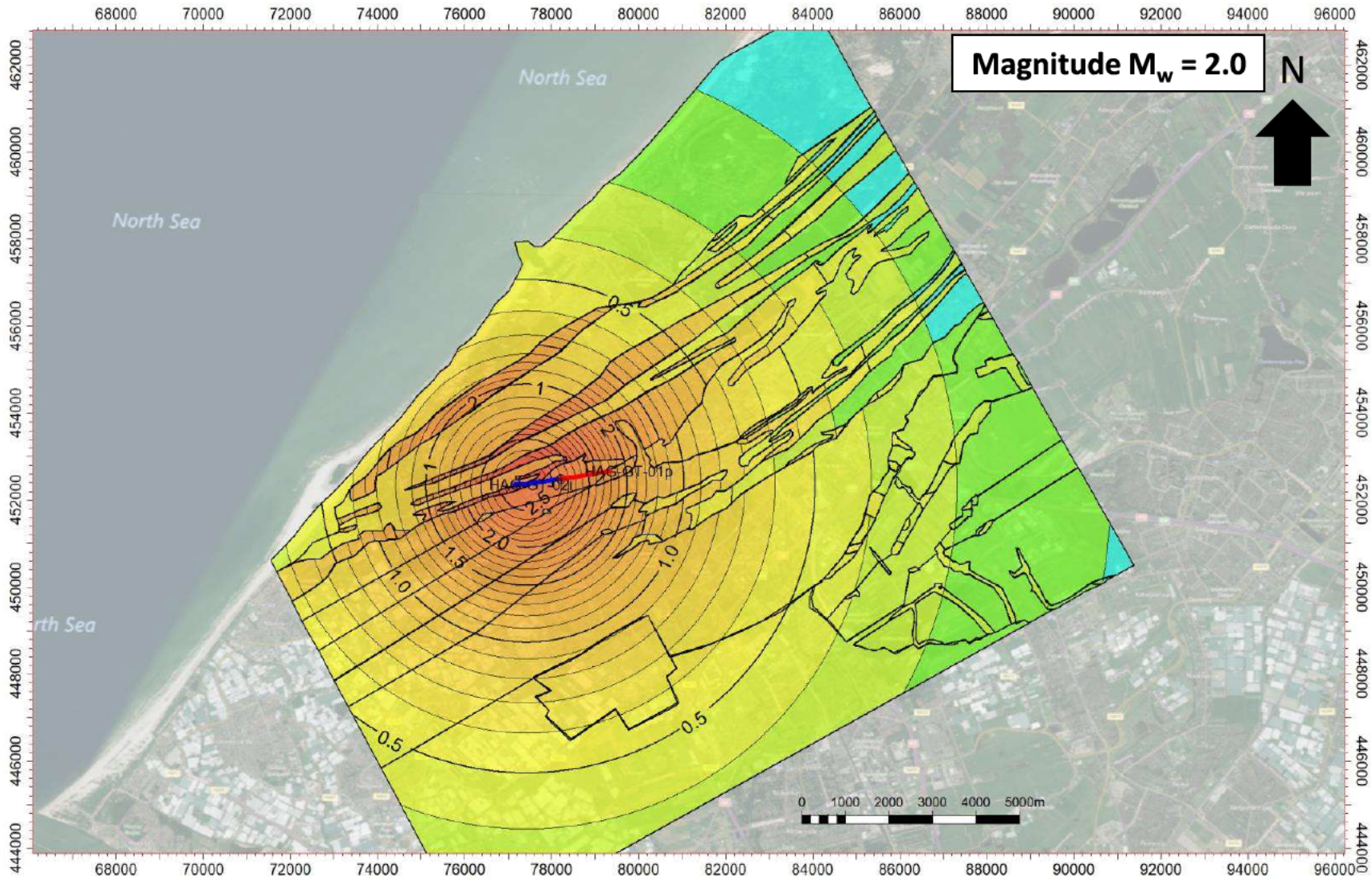
Ground Motion Prediction $M_w = 2.0$

PGV (mm/s)



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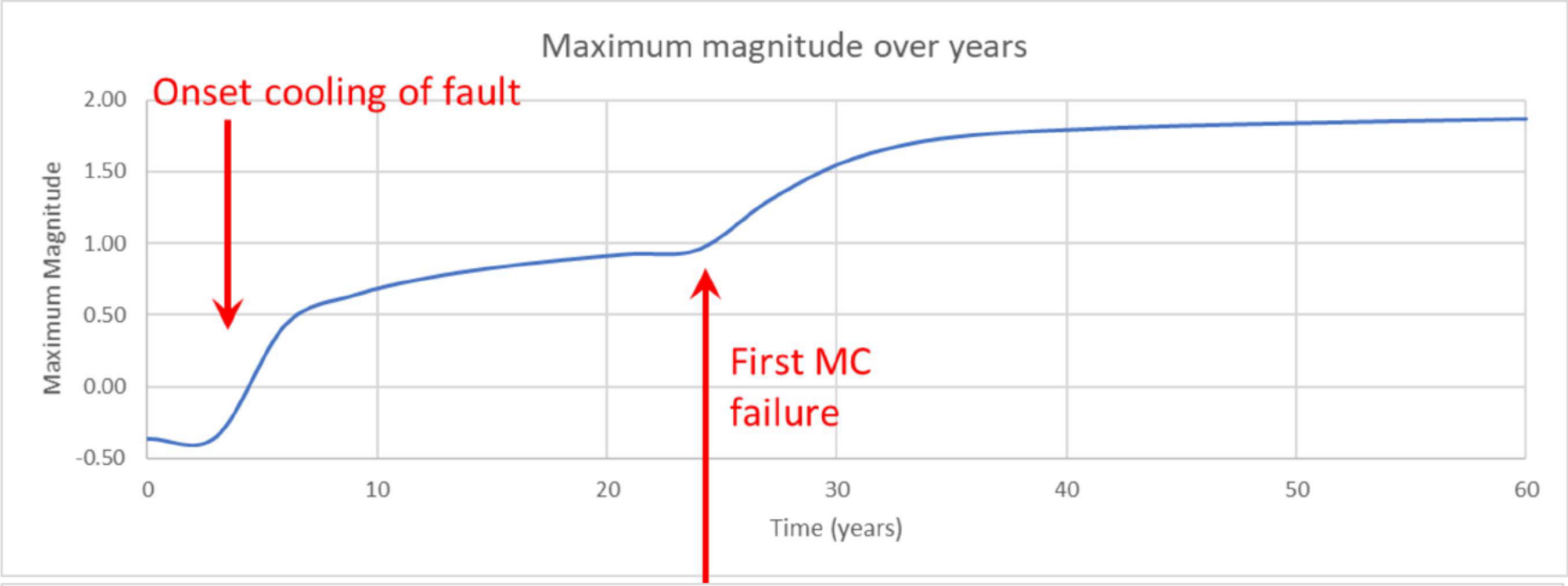
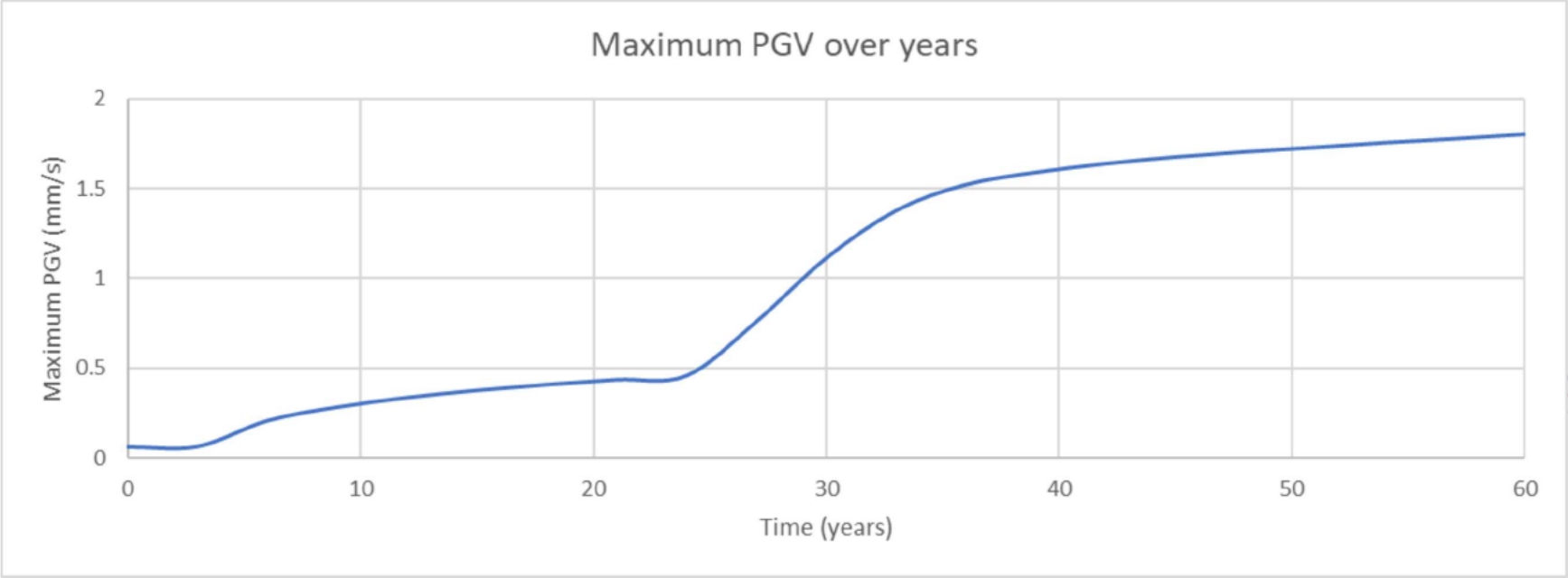
Extreme scenario HAL: Magnitude





Appendix 5:

Depletion vs thermo-elastic effect

Theoretical Background

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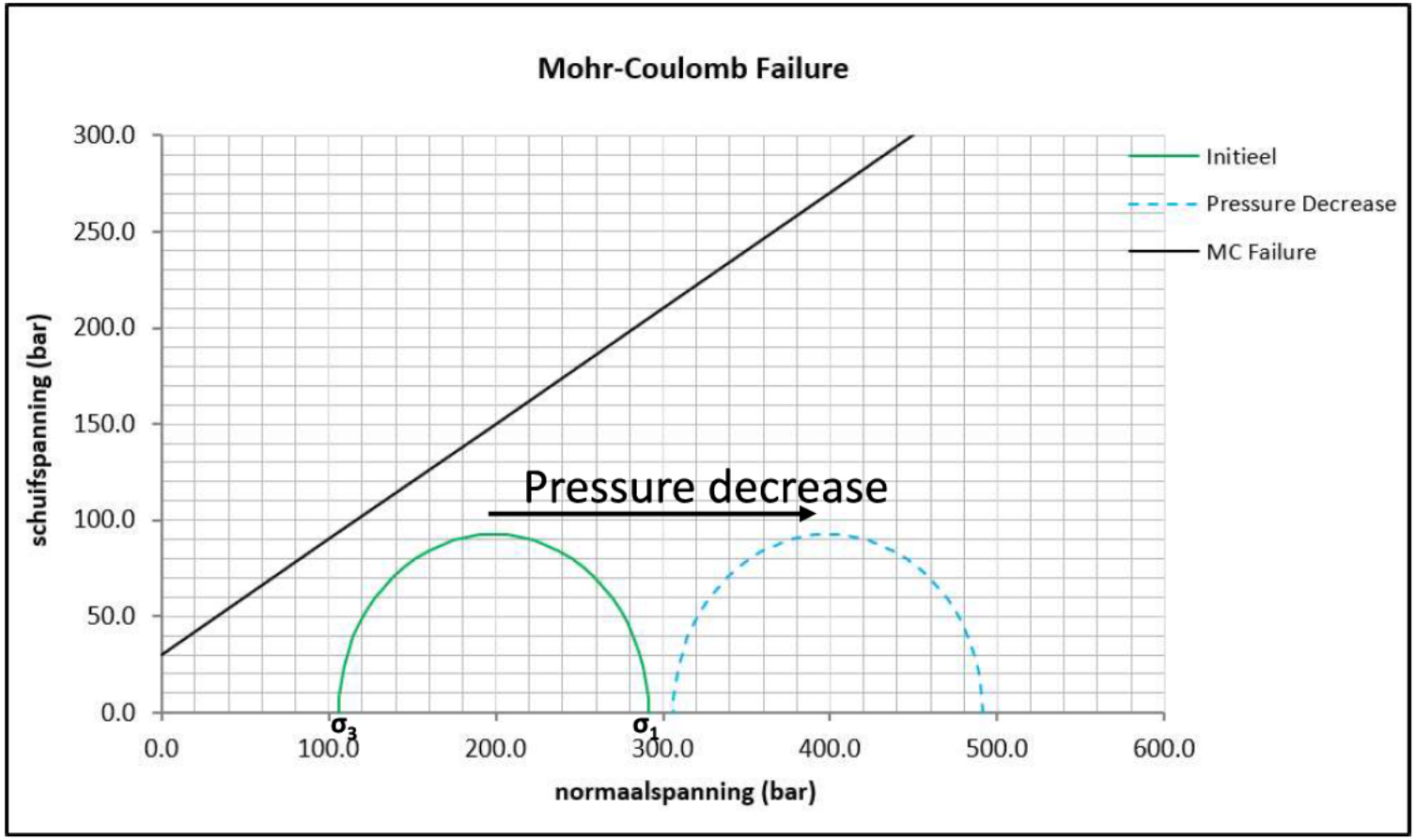
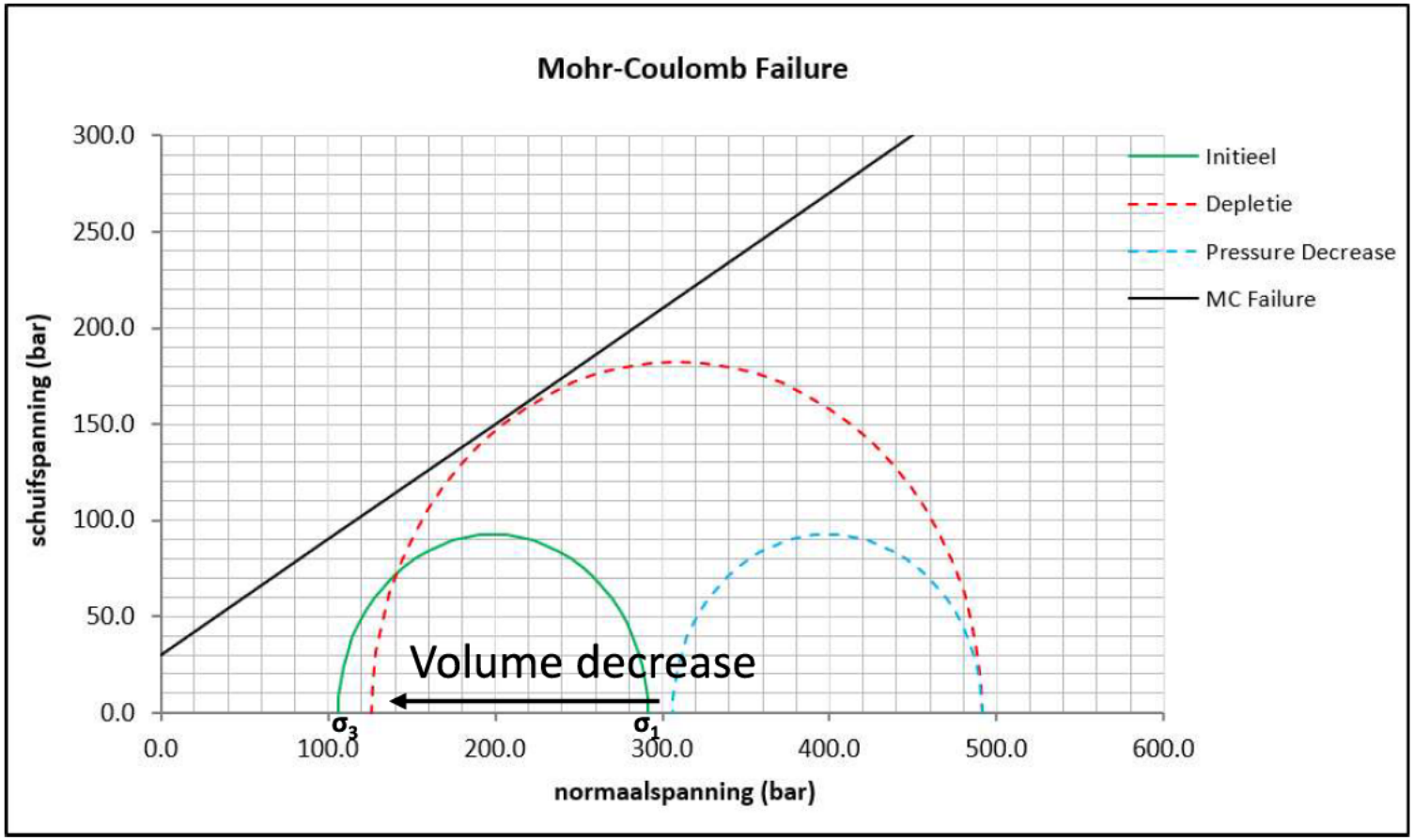
Mohr Coulomb analysis: Depletion (pressure decrease)



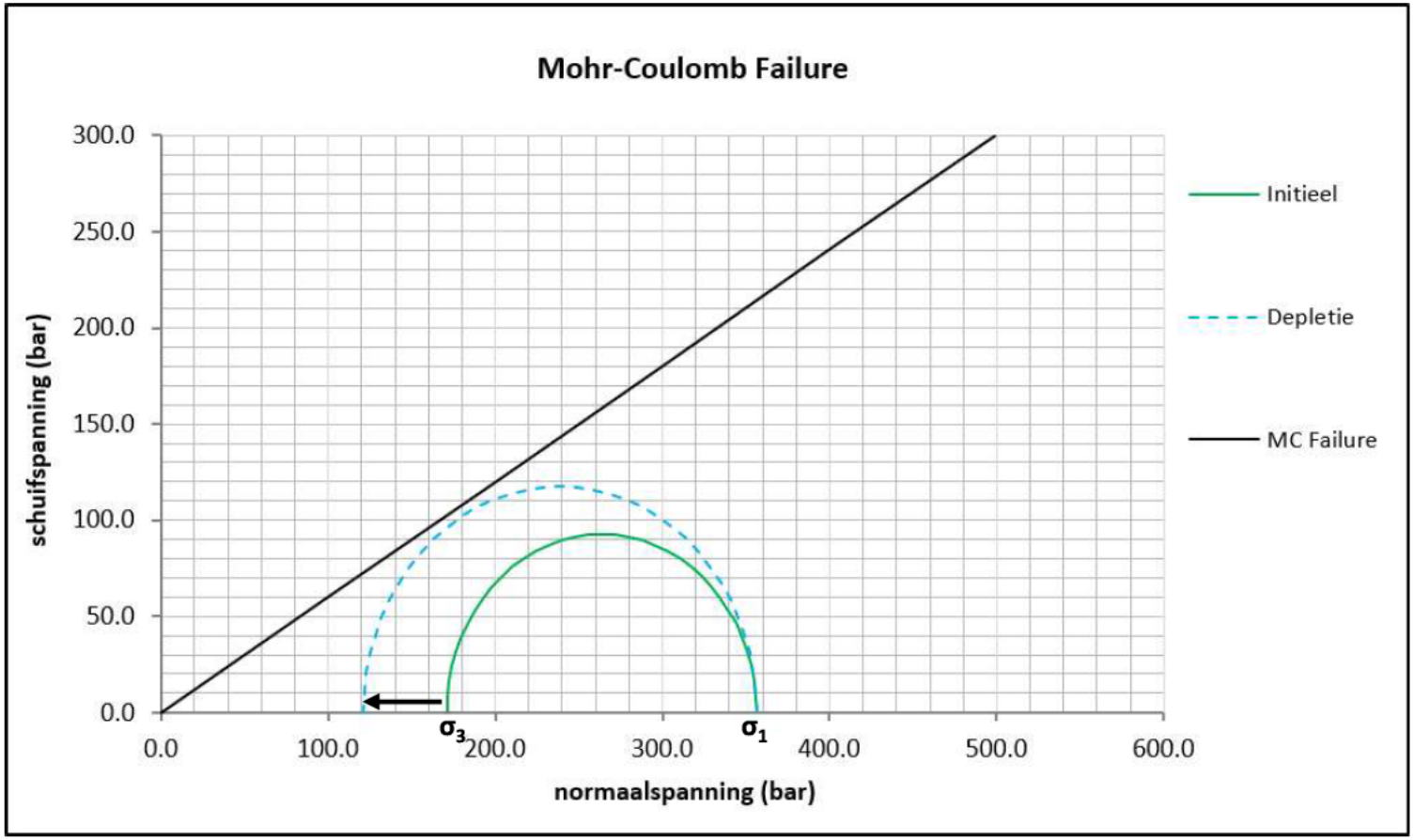
Mohr Coulomb analysis: Depletion (pressure decrease + volume decrease)



$$\Delta\sigma_1 = \Delta p$$

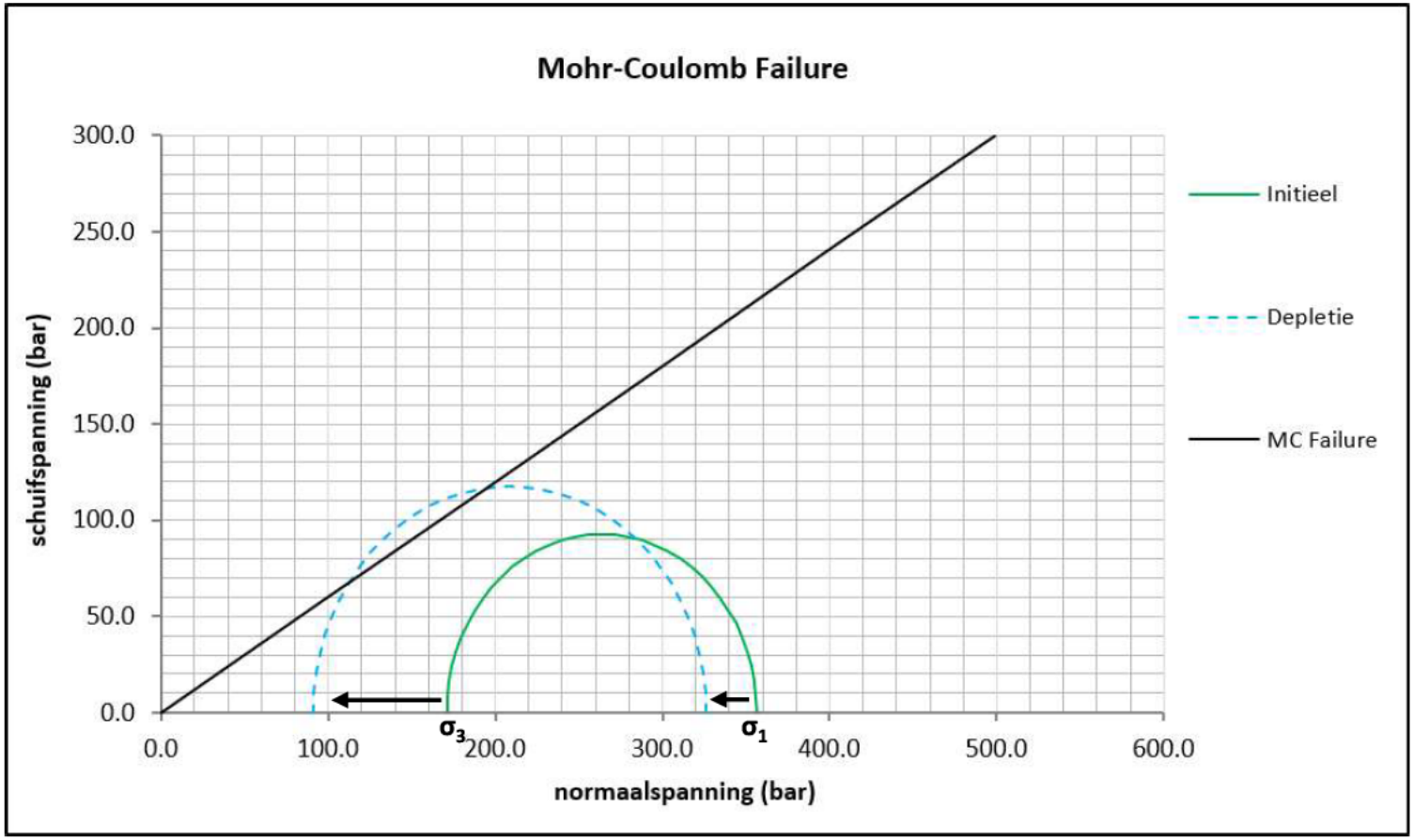
$$\Delta\sigma_3 = \Delta p \frac{v}{1 - v}$$

Mohr-Coulomb analysis: Cooling



Volume decrease due to cooling: $\Delta\sigma'_3 = -\alpha\Delta T\frac{E}{1-v}$

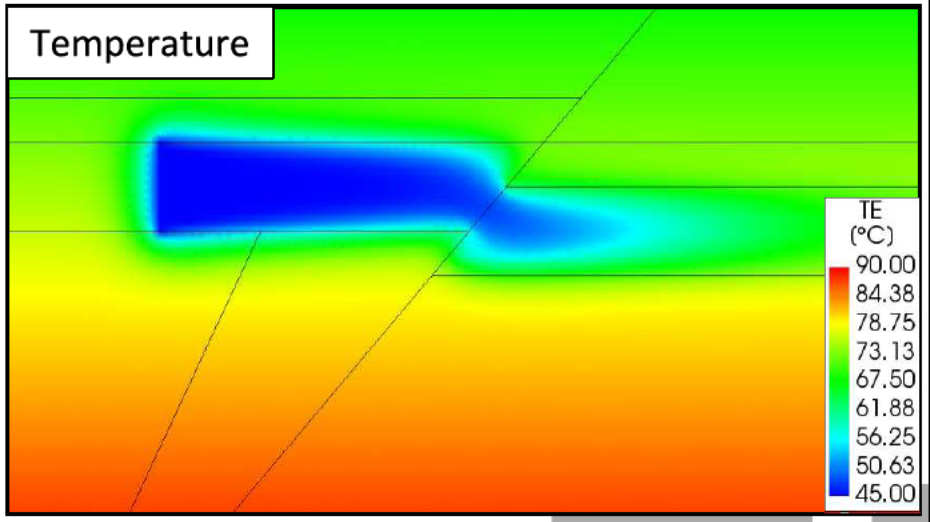
Mohr-Coulomb analysis: Cooling + pressure increase

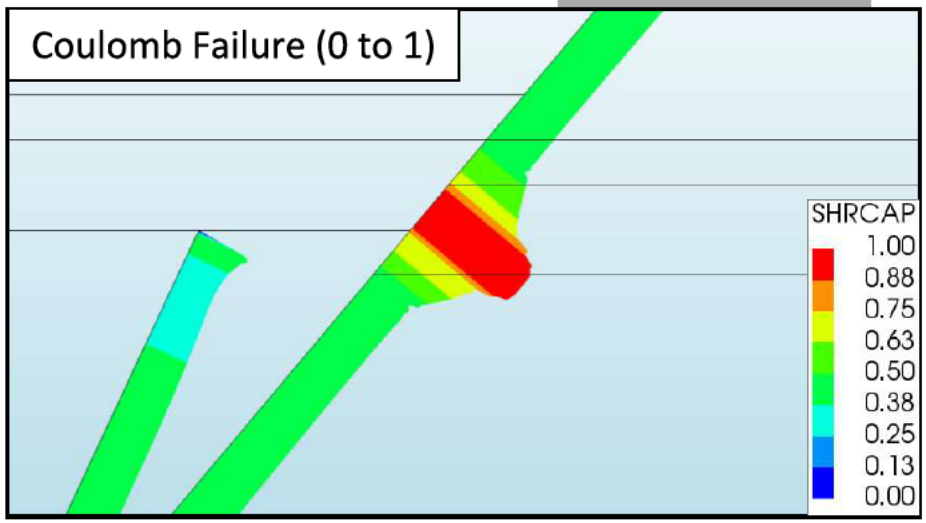


Volume decrease due to cooling & pressure increase: $\Delta\sigma_3 = -(\alpha\Delta T\frac{E}{1-\nu} + \Delta p_f)$

Thermo-elastic effect

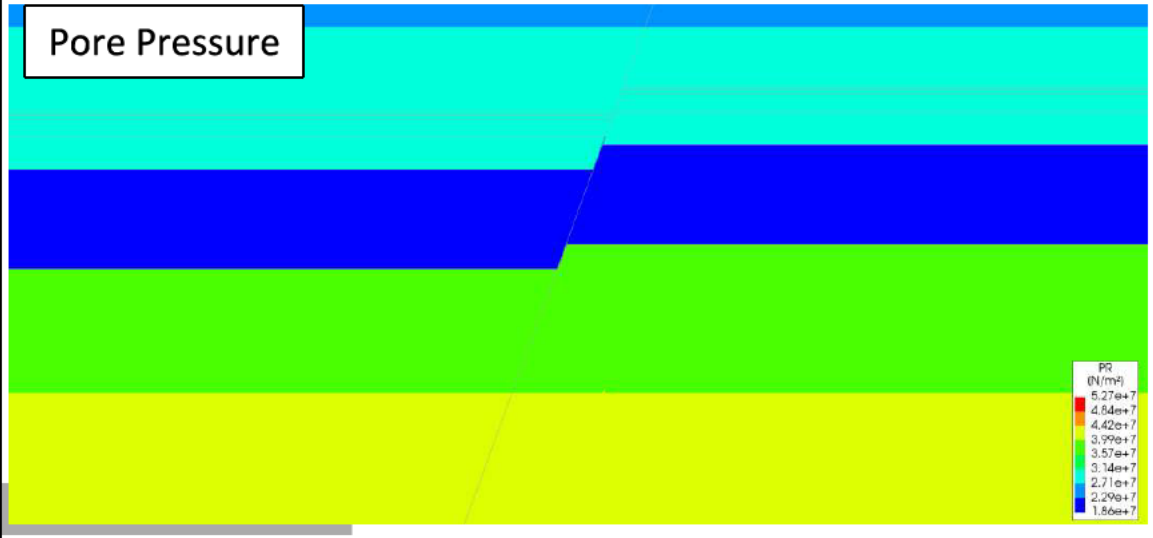
- Thermal cooling in reservoir and diffusion to surrounding layers
- No stress concentrations at lithology boundaries

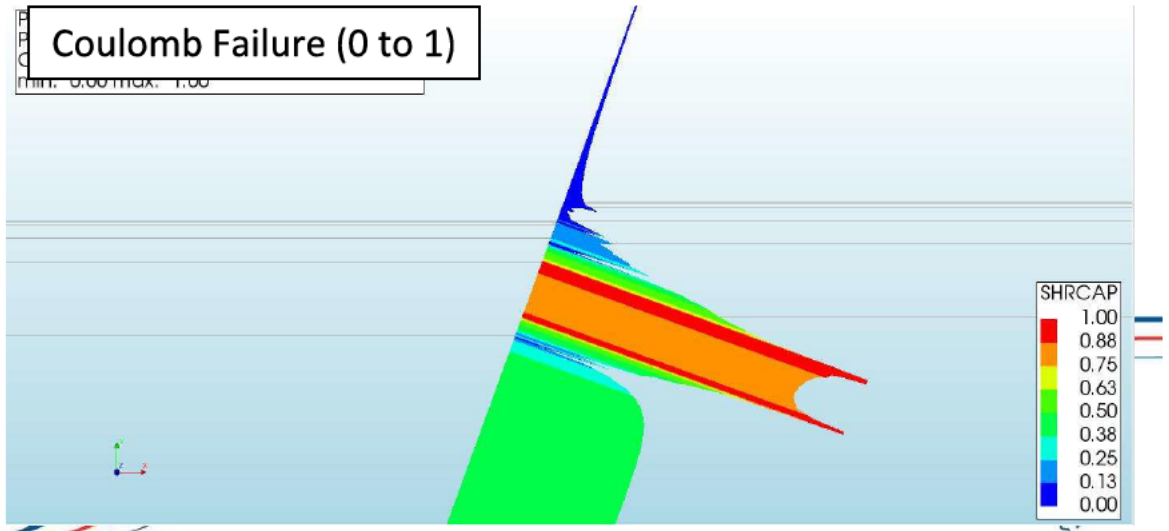




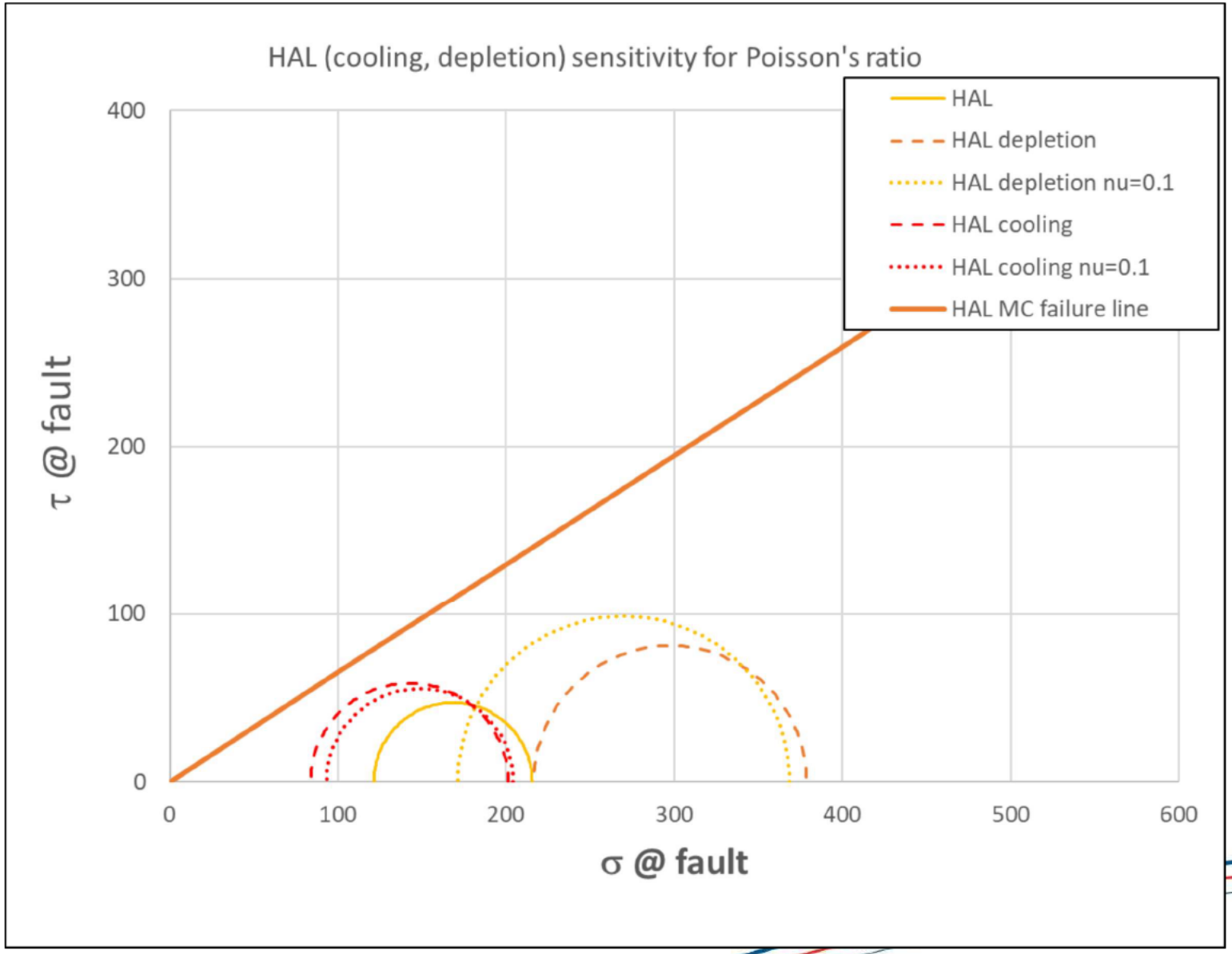
Depletion

- Uniform depletion in reservoir only
- Stress concentrations at lithology boundaries





HAL depletion and cooling: Poisson's ratio



Appendix 6: Magnitude calculation: Theoretical background

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Magnitude Calculation

- Magnitude $M_w = \frac{2}{3} 10_{\log(M_0)} - 6.1$
- $M_0 = \int G \cdot \overline{D} \cdot S$
  - G is the shear modulus
  - $\overline{D}$ is the displacement
  - S is the surface of the fault
- The surface is considered to be 100m by maximum 400m.

SCU (Shear Capacity Utilisation)

- Indicates distance to Mohr Coulomb Failure Line
- $SCU = \frac{\tau}{\tau_{max}} = \frac{\tau}{C+(\sigma_n - P)\mu}$

[redacted]

Appendix 7: Monte Carlo analysis sensitvitity

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