Fully coupled model for chemically induced fault slippage

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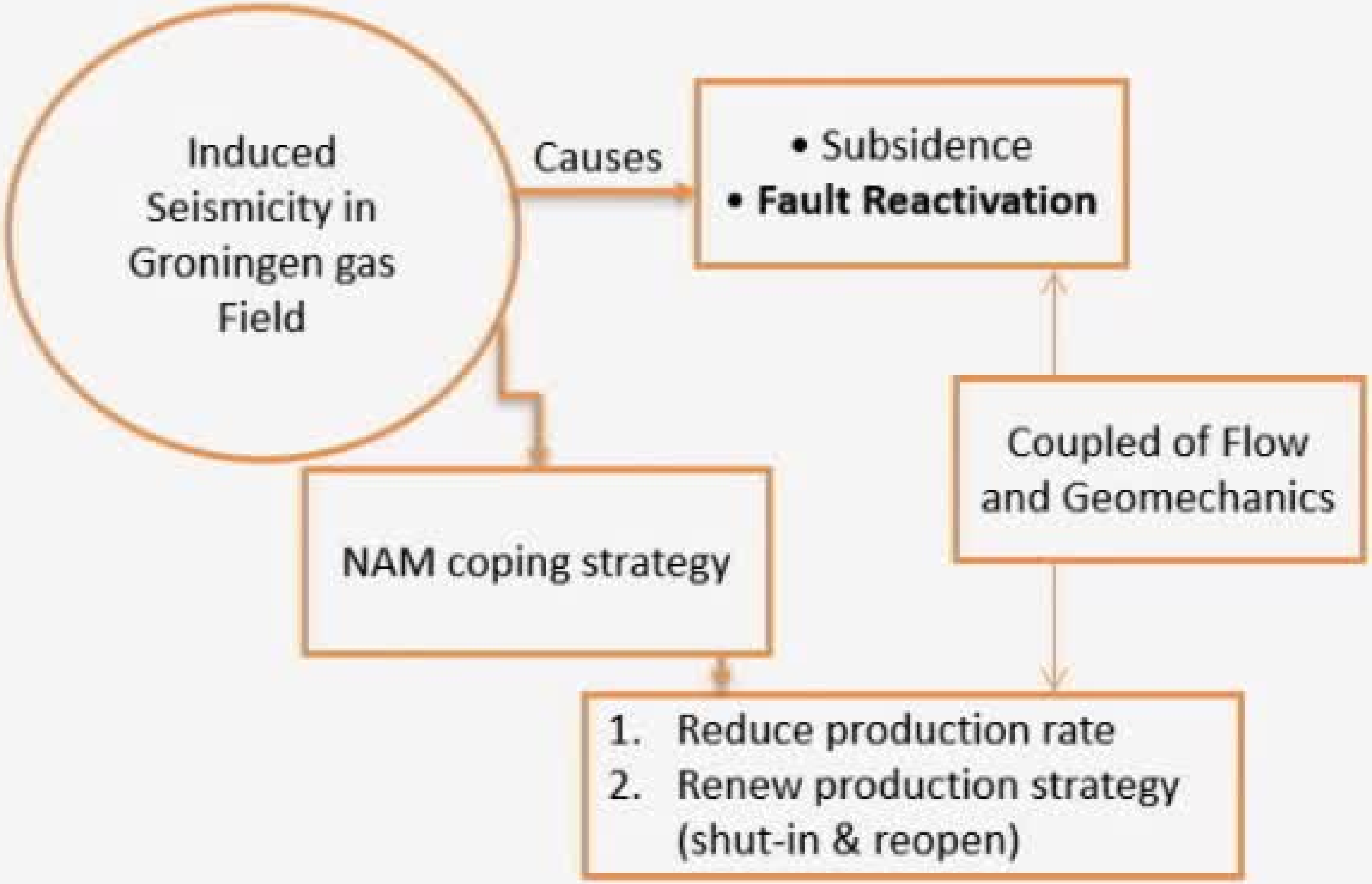
Motivation: Groningen Gas Field

- Groningen gas field is the largest gas producer in the NW Europe
- Discovered by the well at Slochteren (SLO-1) in 1959.
- Has been operating since 1963 by NAM (Nederlandse Aardolie Maatschappij)
- Estimated recoverable gas : ~2,800 Bm^3
- Yearly production 53.9 Bm^3 up to 2013

Induced seismicity

- Largest 3.4 magnitude quake took place in January 2018[1]
- Maximum production of 39.4 Bm^3 in 2016 down to 26.1bm^3 this year.[1]



Induced Seismicity in Groningen gas Field

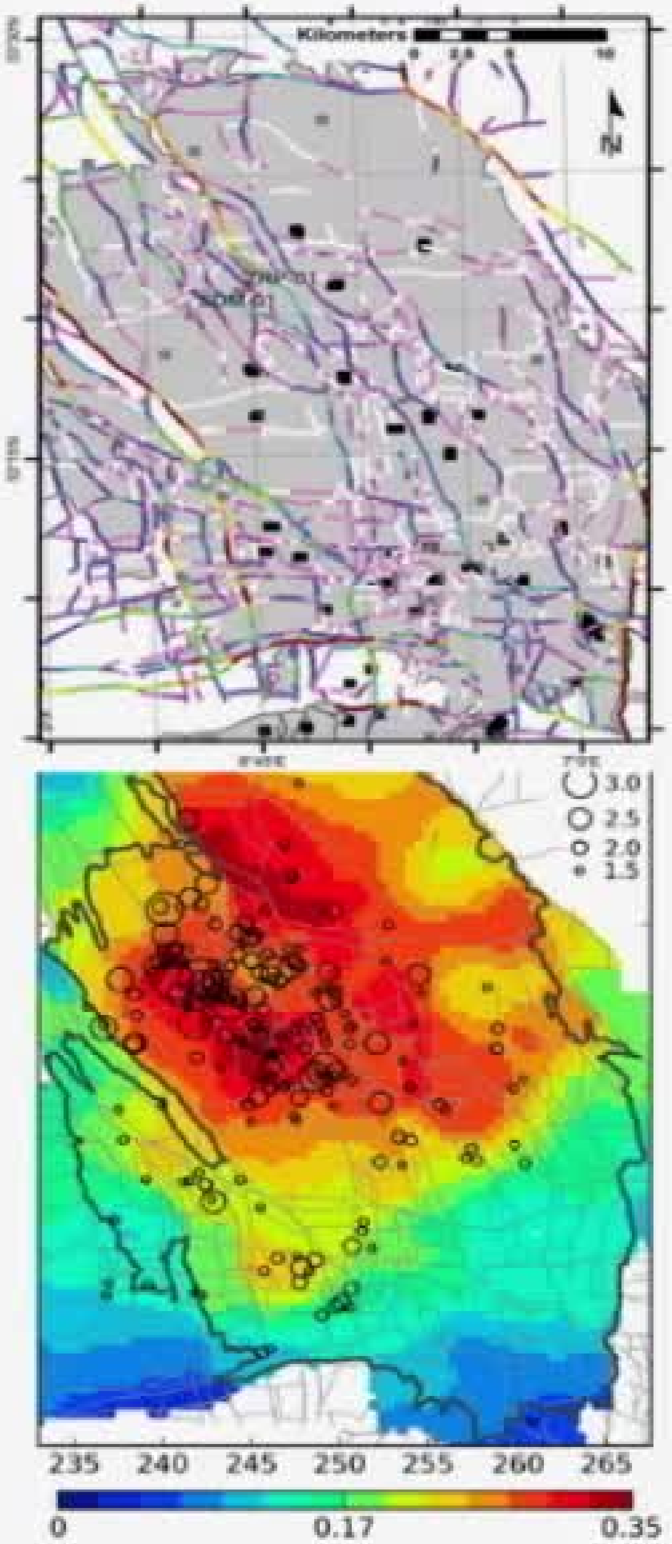
Causes

- Subsidence
- **Fault Reactivation**

NAM coping strategy

Coupled of Flow and Geomechanics

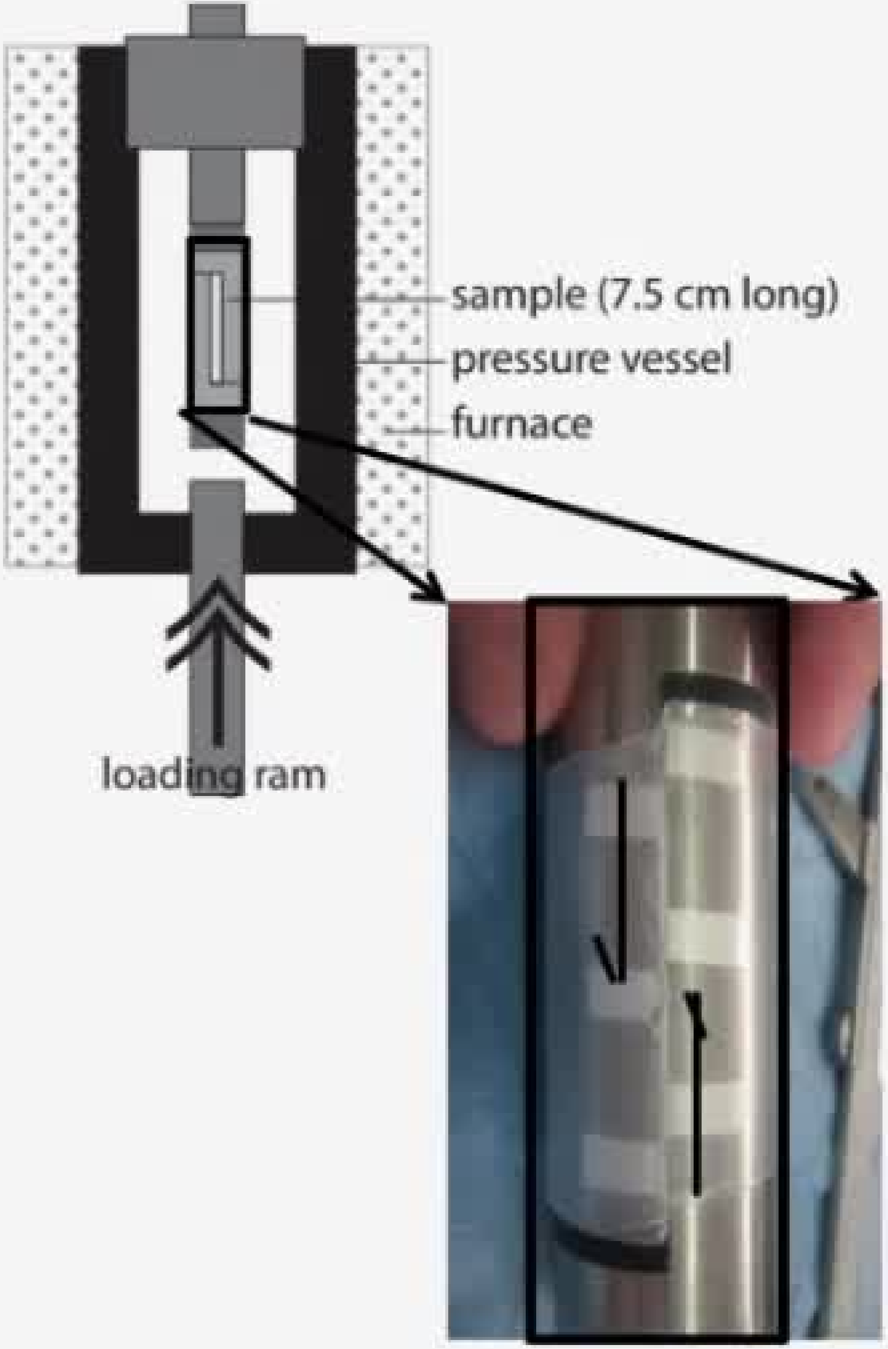
1. Reduce production rate
2. Renew production strategy (shut-in & reopen)

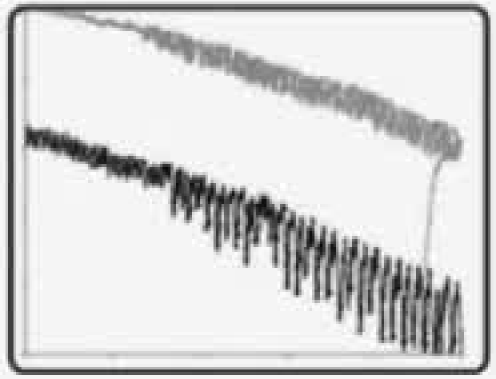


[1] https://phys.org/news/2018-02-dutch-urged-groningen-gas-output.html

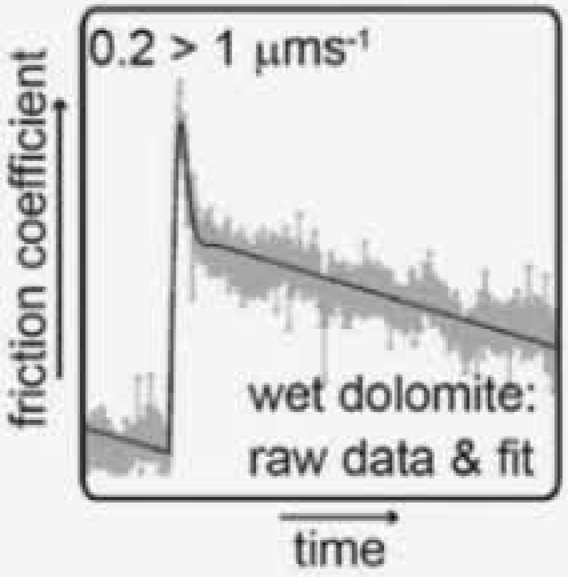
Role of chemistry in fracturing

The effect of water and CO2 on friction in anhydrite and/or dolomite fault gouges at 120°C

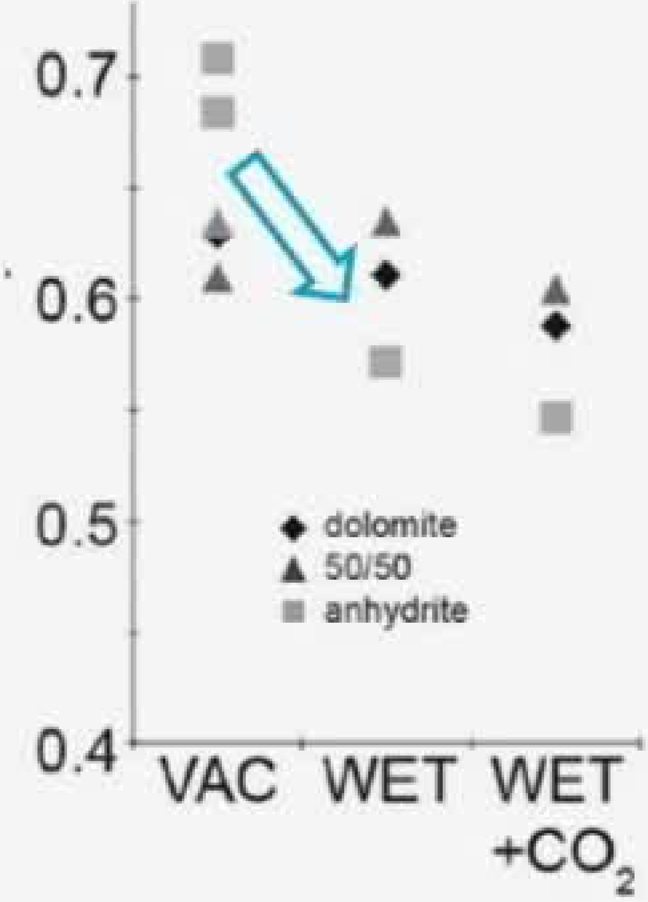




Dry: lab EQ's



Wet (±CO2): stable sliding



Decrease in friction coefficient due to the contact with fluid[2]

[2] Pluymakers, A.M.H., Niemeijer, A.R., Spiers, C.J. Frictional properties of simulated anhydrite-dolomite fault gouge and implications for seismogenic potential (2016) Journal of Structural Geology, 84, pp. 31-46.

Rigorous modelling of faults

For accurate modelling of fault dynamics, several phenomena should be considered:

- Multiphase fluid flow
- Continuous mechanics
- Contact mechanics
- Chemical reactions

Additional numerical requirements:

- Fully coupled simulation
- Fully implicit schemes

ADGPRS: Automatic Differentiation General Purpose Research Simulator

- First prototype for gas injection EOR[3]
- Capabilities for thermal-compositional EOR[4]
- Fully-coupled geomechanics with fractures and effects of plasticity[5]
- Current version - flexible multi-physics research simulation platform[6]
- ADGPRS is the base for 10 PhD and 18 MSc (including 12 at TU Delft) projects completed

[3] Voskov D.V., Younis R.M. Tchelepi H.A., 2009: "General nonlinear solution strategies for multi- phase multi-component EoS based simulation". SPE Reservoir Simulation Symposium 1, 649-663.
[4] Zaydullin, R., Voskov, D.V., James, S.C., Henley, H. and Lucia, A., 2014: Fully compositional and thermal reservoir simulation. *Computers and Chemical Engineering*, 63, 51-65.
[5] Garipov, T.T., Karimi-Fard, M. and Tchelepi, H.A., 2016: Discrete fracture model for coupled flow and geomechanics. Computational Geosciences 20 (1) 149-160.
[6] Garipov, T.T., Tomin, P., Rin, R., Voskov, D.V. and Tchelepi, H.A., 2018: Unified thermo-compositional-mechanical framework for reservoir simulation. Computational Geosciences, 22 (4), pp. 1039-1057.

Reactive-compositional flow and transport

Mass balance for fluid components[7]:

$$\frac{\partial}{\partial t}(\phi \rho_T z_i) + \nabla \cdot \sum_{j=1}^{n_p} (\rho_j x_{ij} \vec{v}_j - \rho_j S_j \phi D_{ij} \nabla x_{ij}) = \sum_{k}^{n_r} \nu_{ik} r_k$$

DBS or Darcy:

$$-\nabla p + \frac{\mu_j}{\phi} \Delta \vec{v}_j - \frac{\mu_j}{K} \vec{v}_j = 0$$

$$\vec{v}_j = -\frac{K k_{rj}(S_j)}{\mu_j} \nabla p = -K \lambda_j \nabla p_j$$

Mass balance for solids:

$$\frac{\partial C_s}{\partial t} = \sum_{k}^{n_r} \nu_{sk} r_k$$

Simple kinetic reaction:

Brine + Solid → Product

$$r = \alpha C_s z_a$$

- Finite-volume discretization
- Fully coupled formulation

[7] Tomin, P., Voskov, D., 2018: Robust And Accurate Formulation For Modeling Of Acid Stimulation, ECMOR XVI-16th European Conference on the Mathematics of Oil Recovery.

Discrete Fracture Model

- Flow equation

$$\frac{\partial(\rho_f \phi)}{\partial t} - \nabla \cdot \left[\rho_f \frac{\boldsymbol{k}}{\mu_f}(\nabla p - \rho_f \boldsymbol{g})\right] + \boldsymbol{q} = 0$$

- Finite Volume Method for flow and transport
- Fracture segments have separate volumes

- -

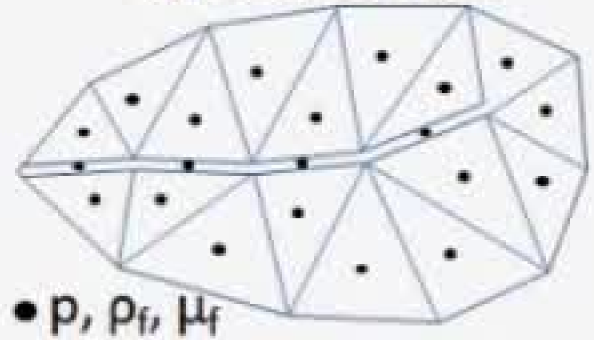
- Momentum conservation equation

$$\nabla \cdot \boldsymbol{\sigma} + \rho \boldsymbol{g} = 0$$

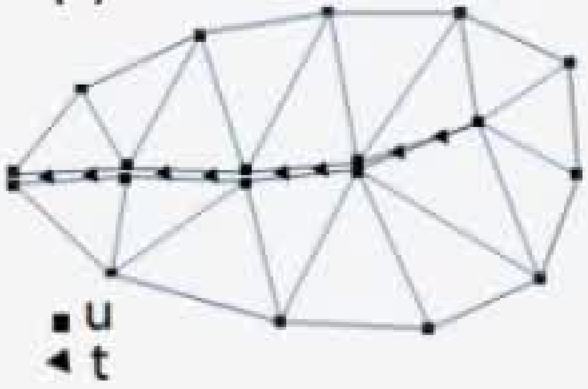
- Finite Element Method
- Fracture modelled as a contact of two surfaces
- The system of equations solved implicitly

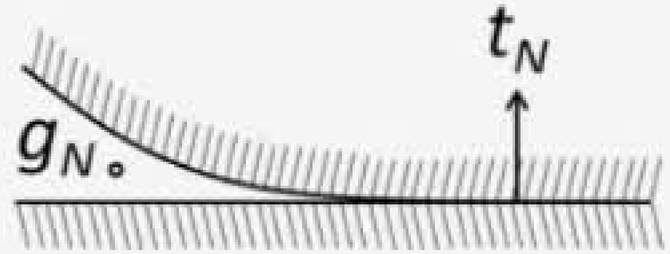
(a)Physical domain

(b)Grid for flow



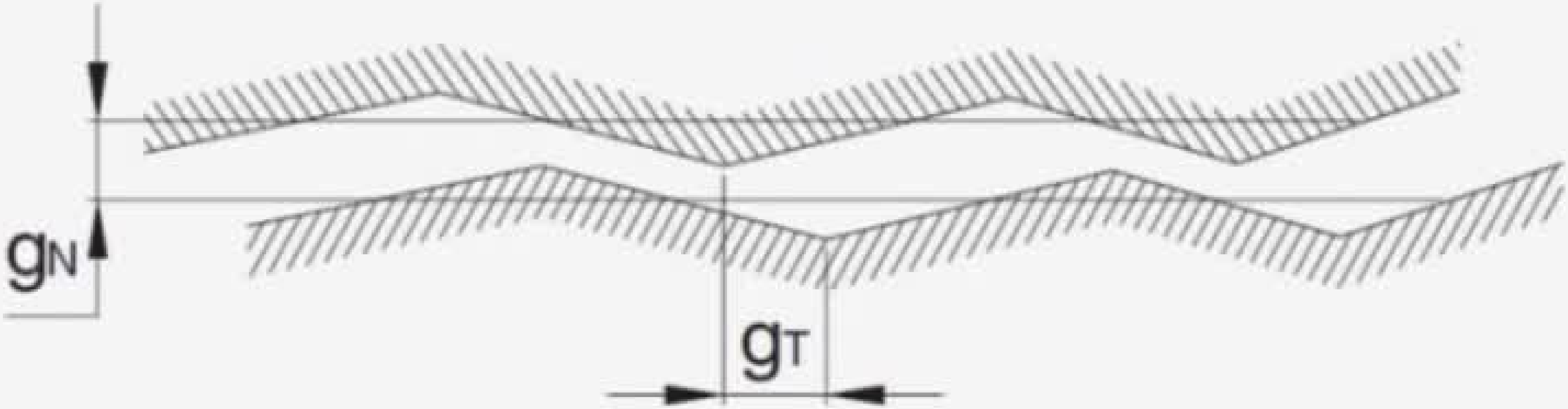
(c)Grid for mechanics





$g_N \geq 0, \quad t_N \geq 0, \quad g_N \cdot t_N \geq 0$

Two surfaces in contact



- Following relations represents open regime[8]:

$$t_{\mathrm{N}} = 0 \text{ and } g_{\mathrm{N}} < 0, \quad \text{open fracture}$$

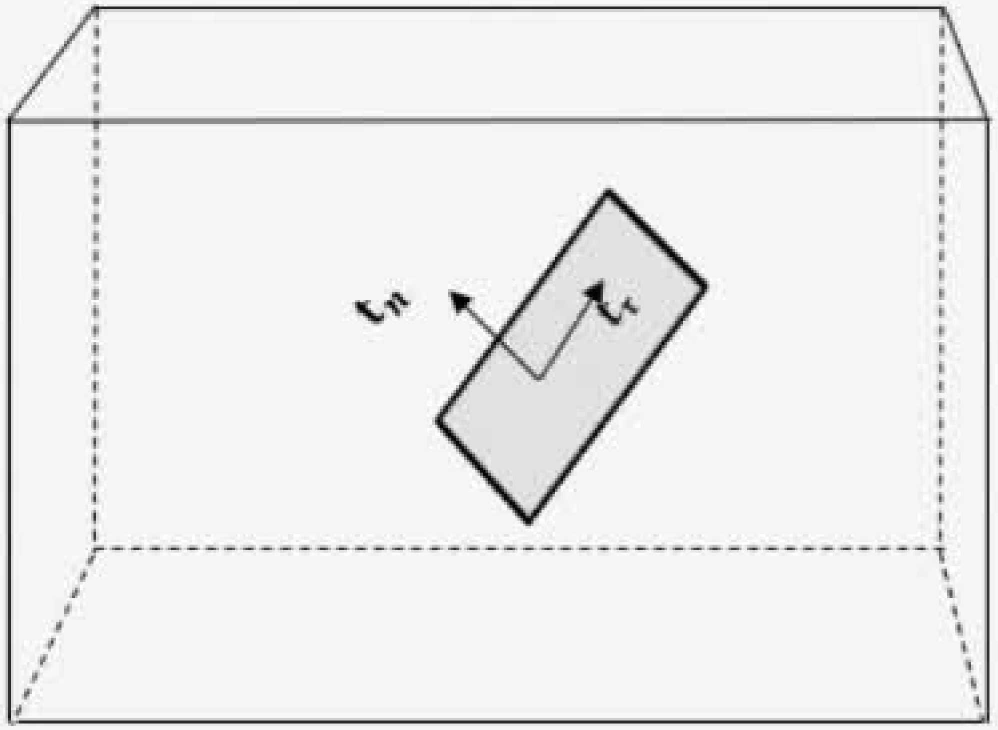
$$t_{\mathrm{T}} < \mathcal{F}(t_{\mathrm{N}}),\ \dot{g}_{\mathrm{T}} = 0, \text{ and } g_{\mathrm{N}} = 0, \quad \text{stick state}$$

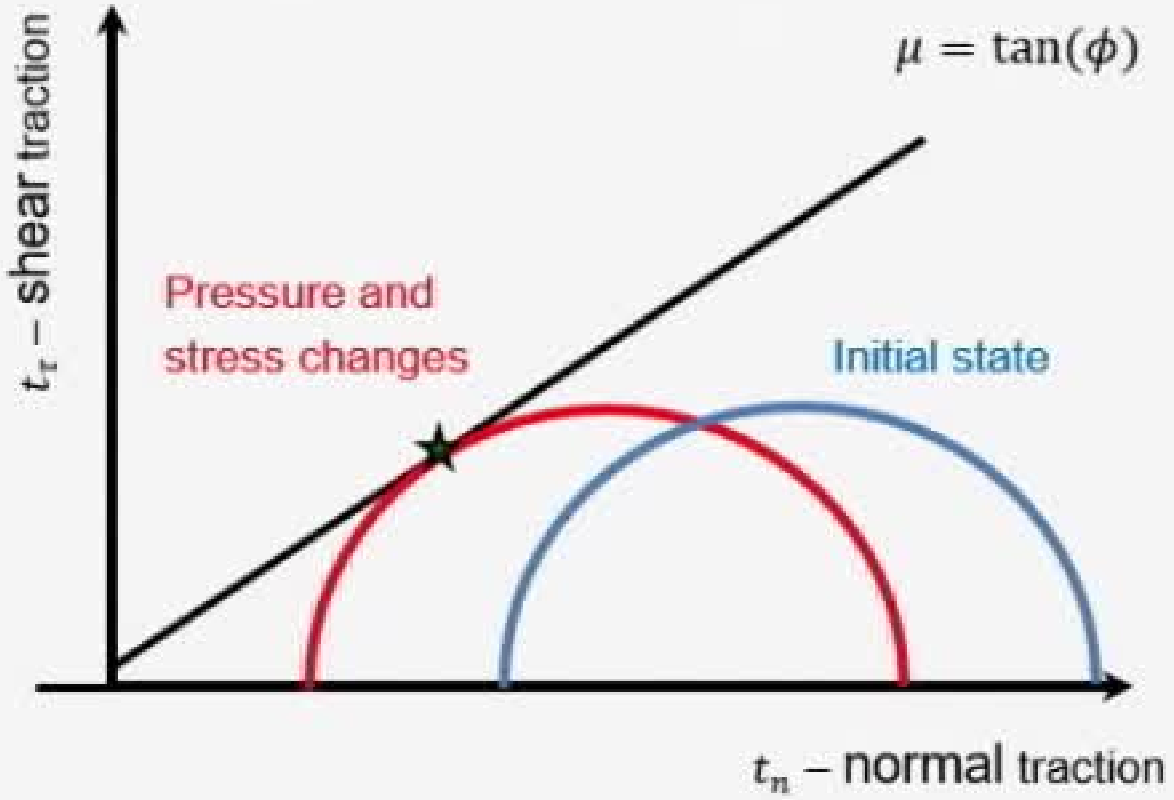
$$t_{\mathrm{T}} = \mathcal{F}(t_{\mathrm{N}}),\ \dot{g}_{\mathrm{T}} > 0, \text{ and } g_{\mathrm{N}} = 0, \quad \text{slip state}$$

[8] Gallyamov, E., Garipov, T., Voskov, D., Van den Hoek, P., 2018: Discrete fracture model for simulating waterflooding processes under fracturing conditions, International Journal for Numerical and Analytical Methods in Geomechanics, 42 (13), pp. 1445-1470.

Mathematical Model of a Fault

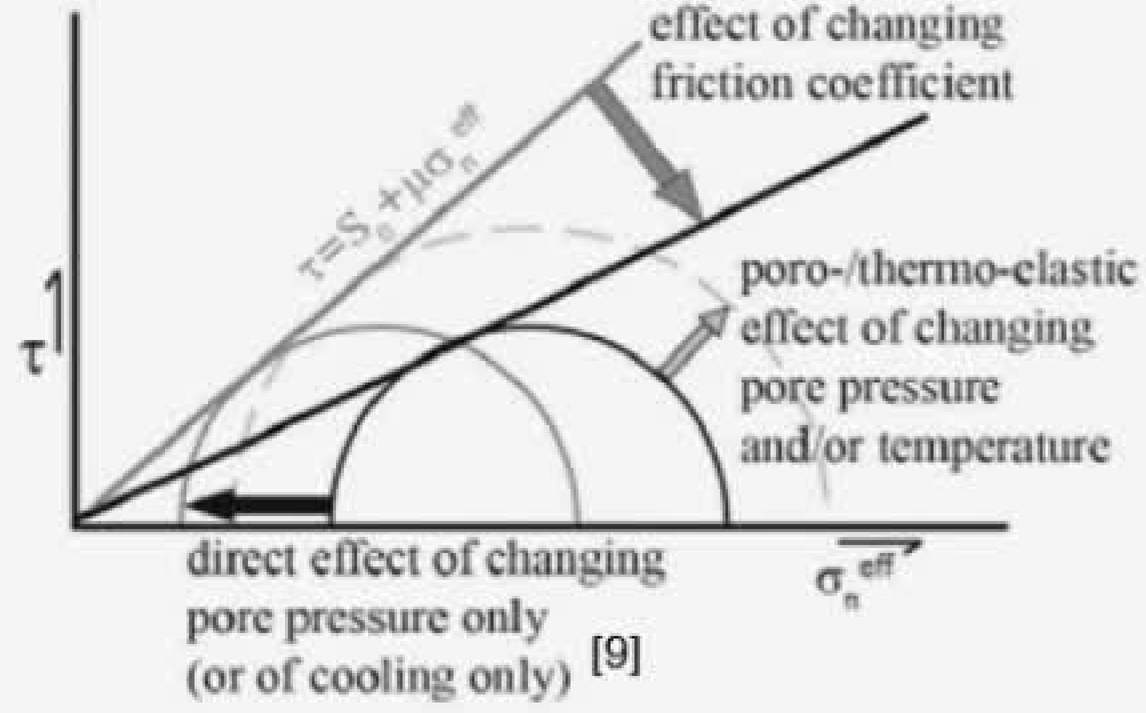
- A fault is represented as two surfaces in contact
- The DFM approach is used to model fault activation
- Activation occurs due to change of fluid pressure and also depends on minerals concentration



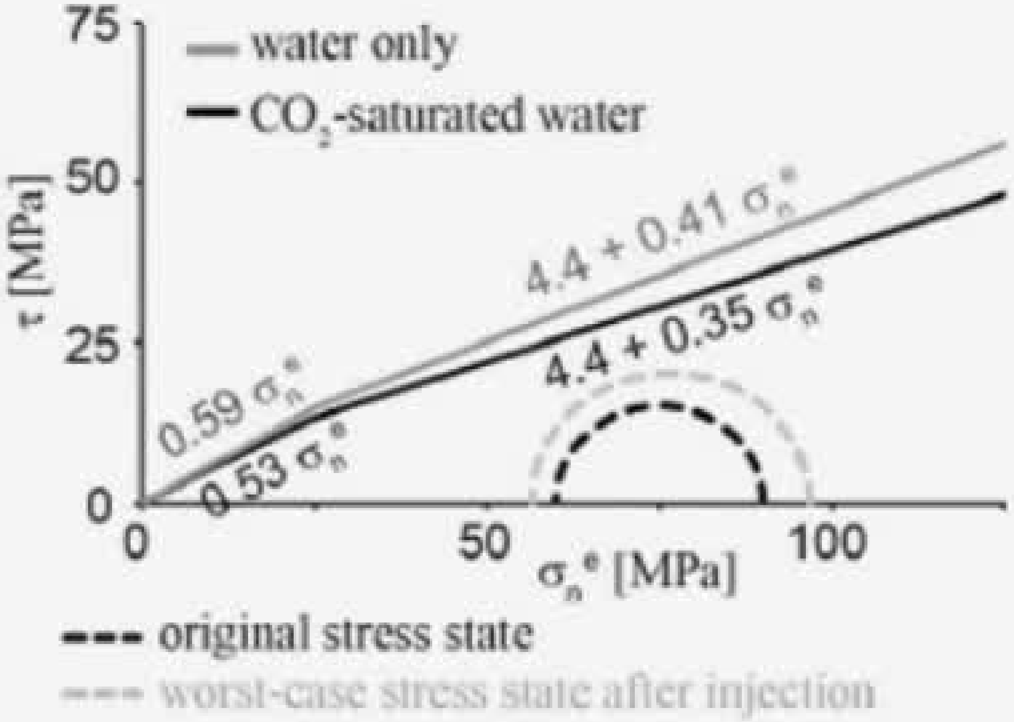


Mohr-Coulomb

Friction dependency on chemistry



[9]

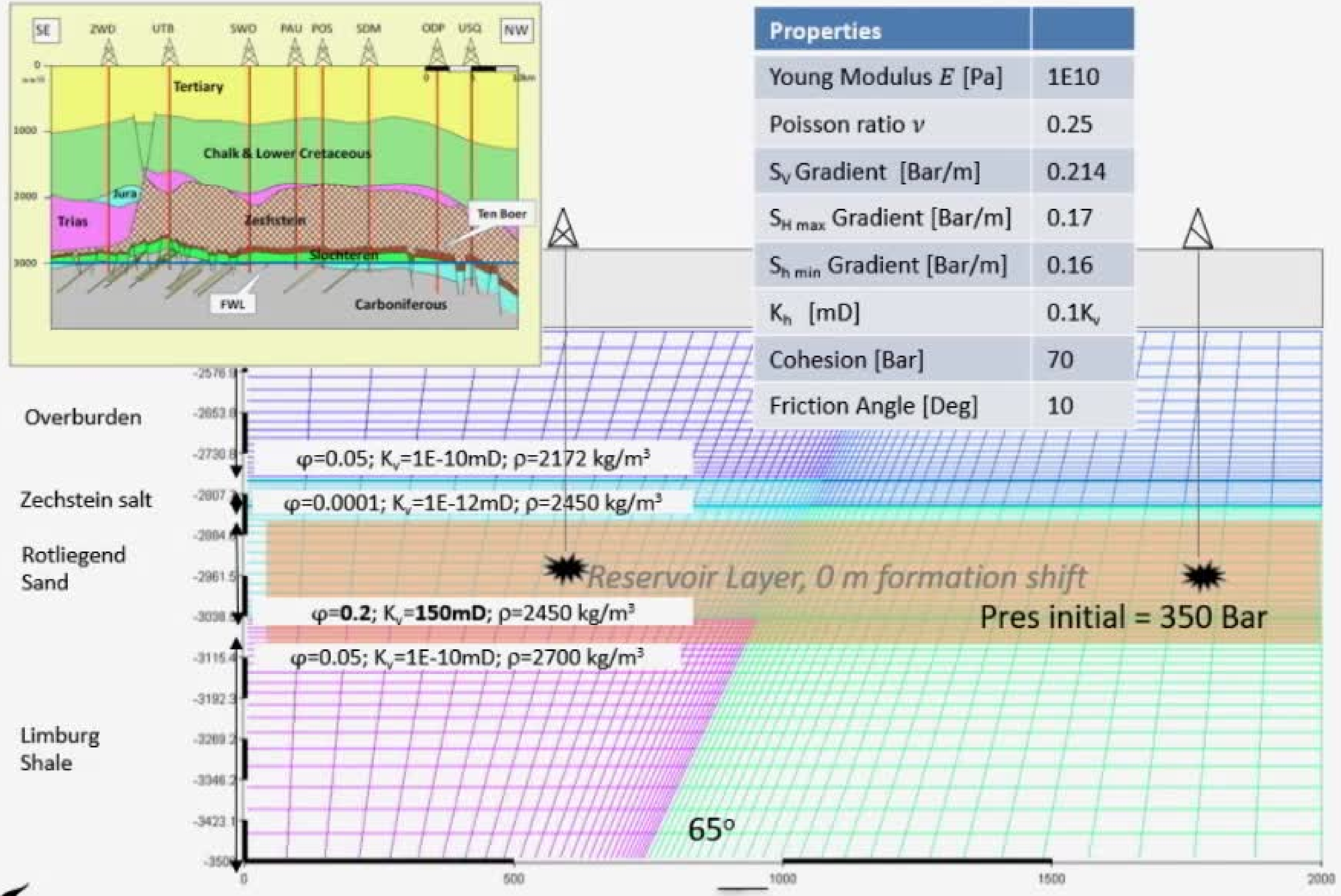


Friction reduction due to minerals concentration change:

$$\mu = \mu_{init}\left(1 - \alpha\frac{C_0 - C}{C_0}\right)$$

[9] Rohmer, J., Pluymakers, A., Renard, F., 2016: Mechano-chemical interactions in sedimentary rocks in the context of CO2 storage: Weak acid, weak effects? Earth-Science Reviews, 157, pp. 86-110.

Validation of the simulation framework

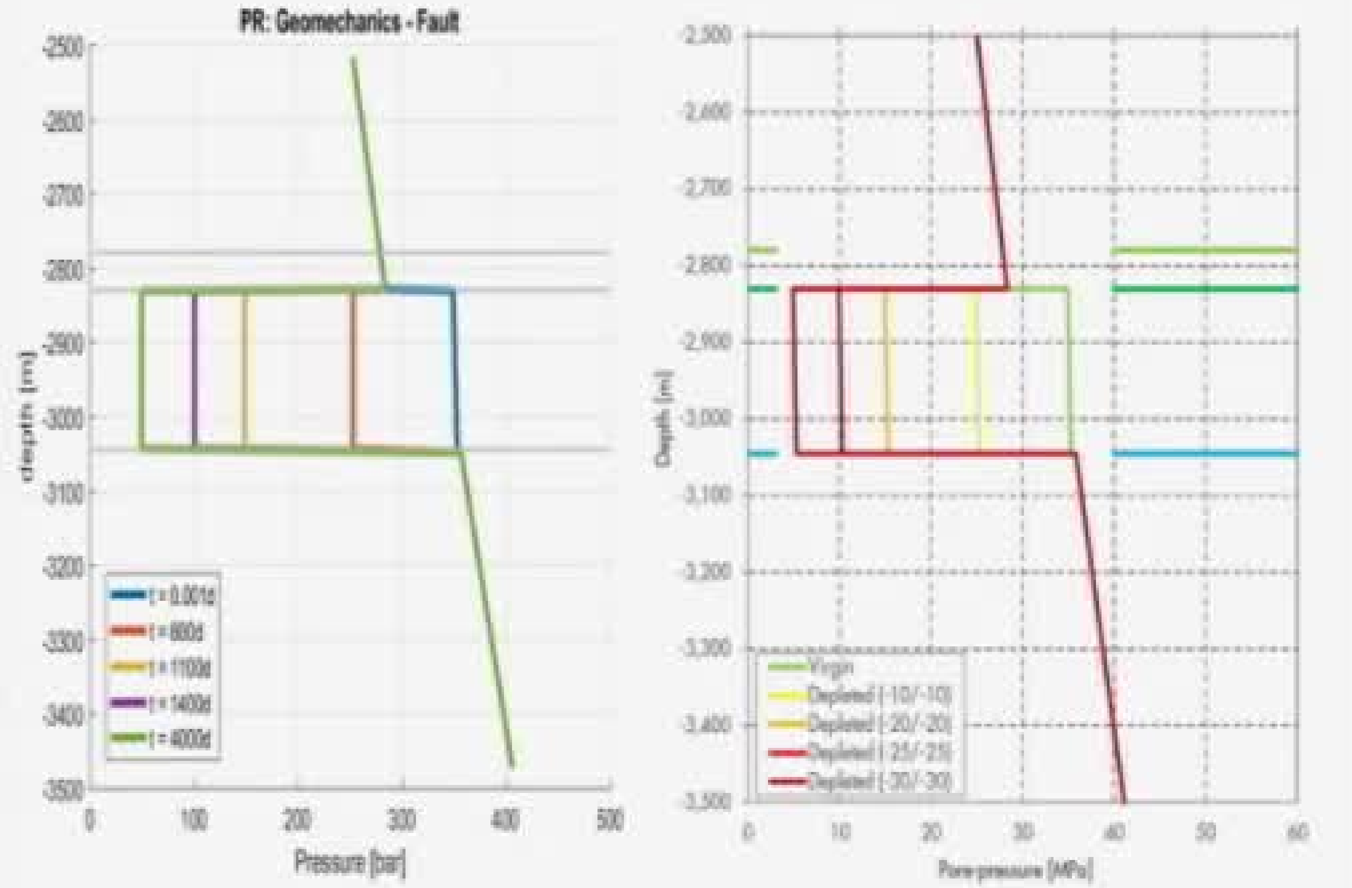


Properties	
Young Modulus E [Pa]	1E10
Poisson ratio ν	0.25
S_v Gradient [Bar/m]	0.214
$S_{H\,max}$ Gradient [Bar/m]	0.17
$S_{h\,min}$ Gradient [Bar/m]	0.16
K_h [mD]	$0.1K_v$
Cohesion [Bar]	70
Friction Angle [Deg]	10

Solution comparison: pressure and tractions

- Validation against simulation study performed in NAM[10]
- In addition to validation, the effect of dynamic was studied[11]

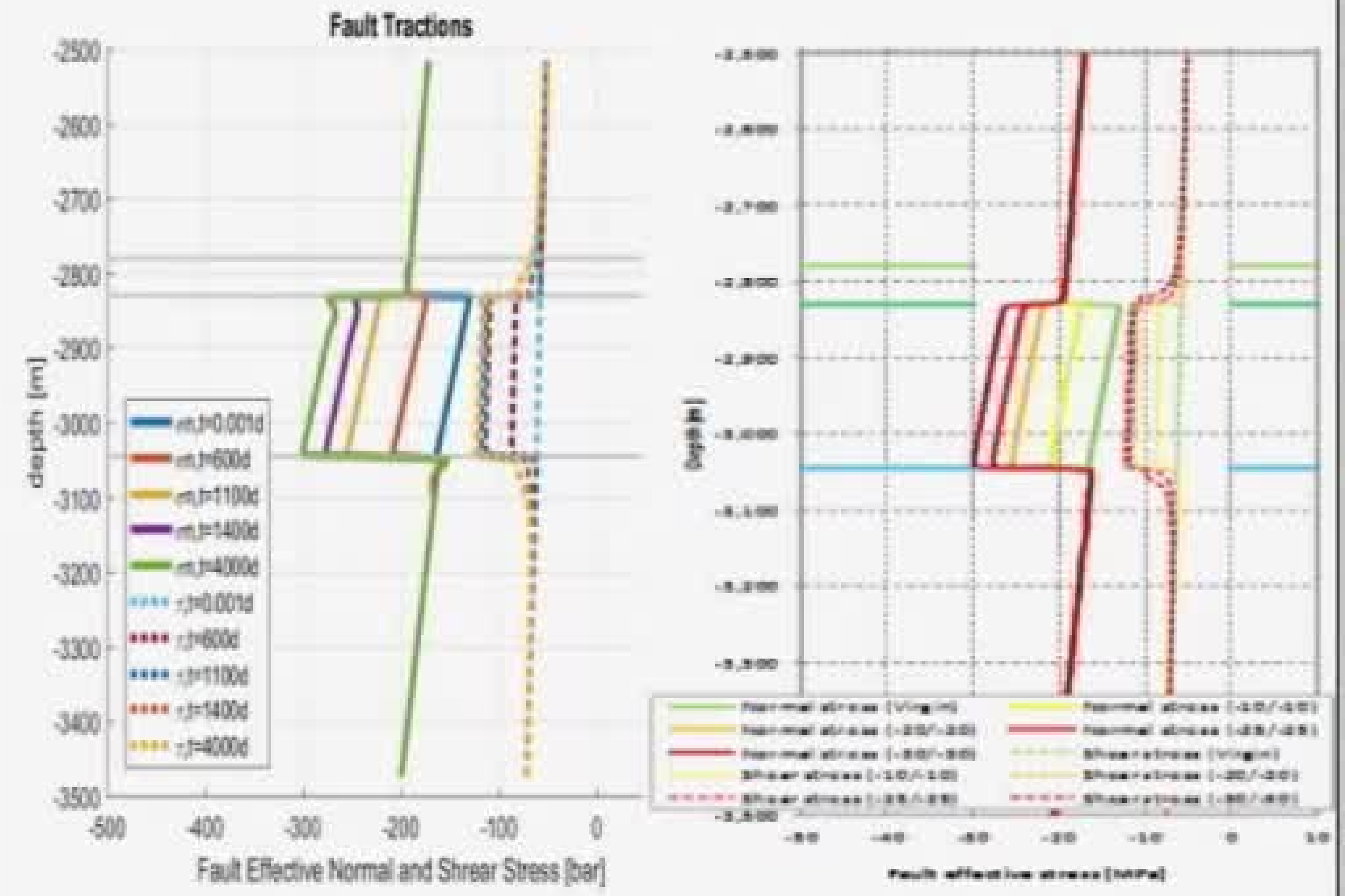
Pressure along the fault surface



ADGPRS result

Reference [10]

Tractions acting on the fault



ADGPRS result

Reference [10]

[10] Bogert ,P.A.J. van den., 2015: Impact of various modelling options on the onset of fault slip and the fault slip response using 2-dimensional Finite Element modelling, NAM report.

[11] Ihsan, G.K., 2018: *Study on the effect of production dynamic to fault reactivation*. MSc thesis. Delft University of Technology, The Netherlands.

Solution comparison: shear stresses

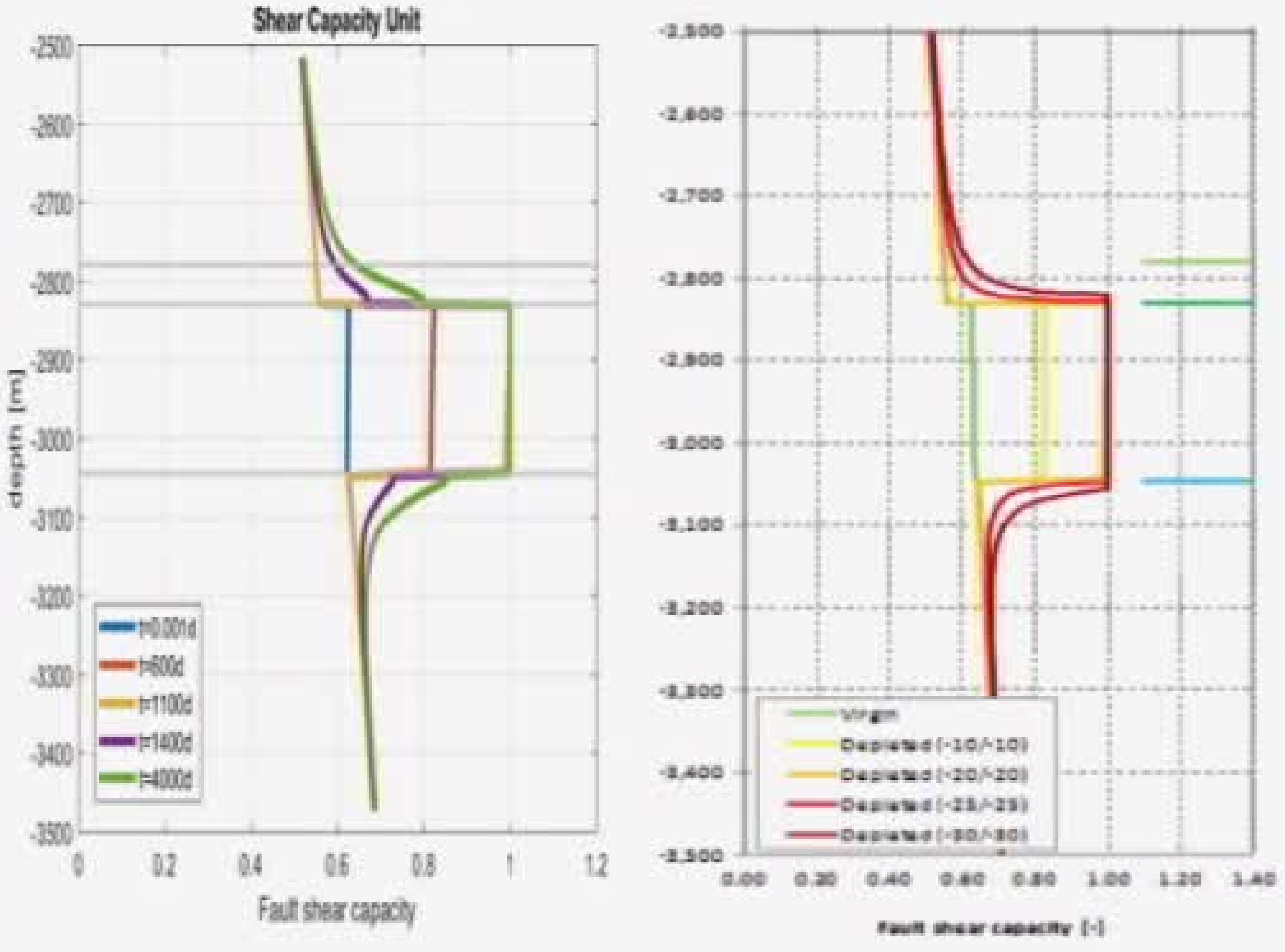
$$SCU = \frac{\tau}{\tau_{max}} = \frac{\tau}{C + \mu\sigma_n}$$

SCU < 1 → behaves elastically
SCU = 1 → plastic behaviour

$$du = u_+ - u_-$$

$$g(n,t) = (du)\begin{pmatrix} \boldsymbol{n} \\ \boldsymbol{t} \end{pmatrix}$$

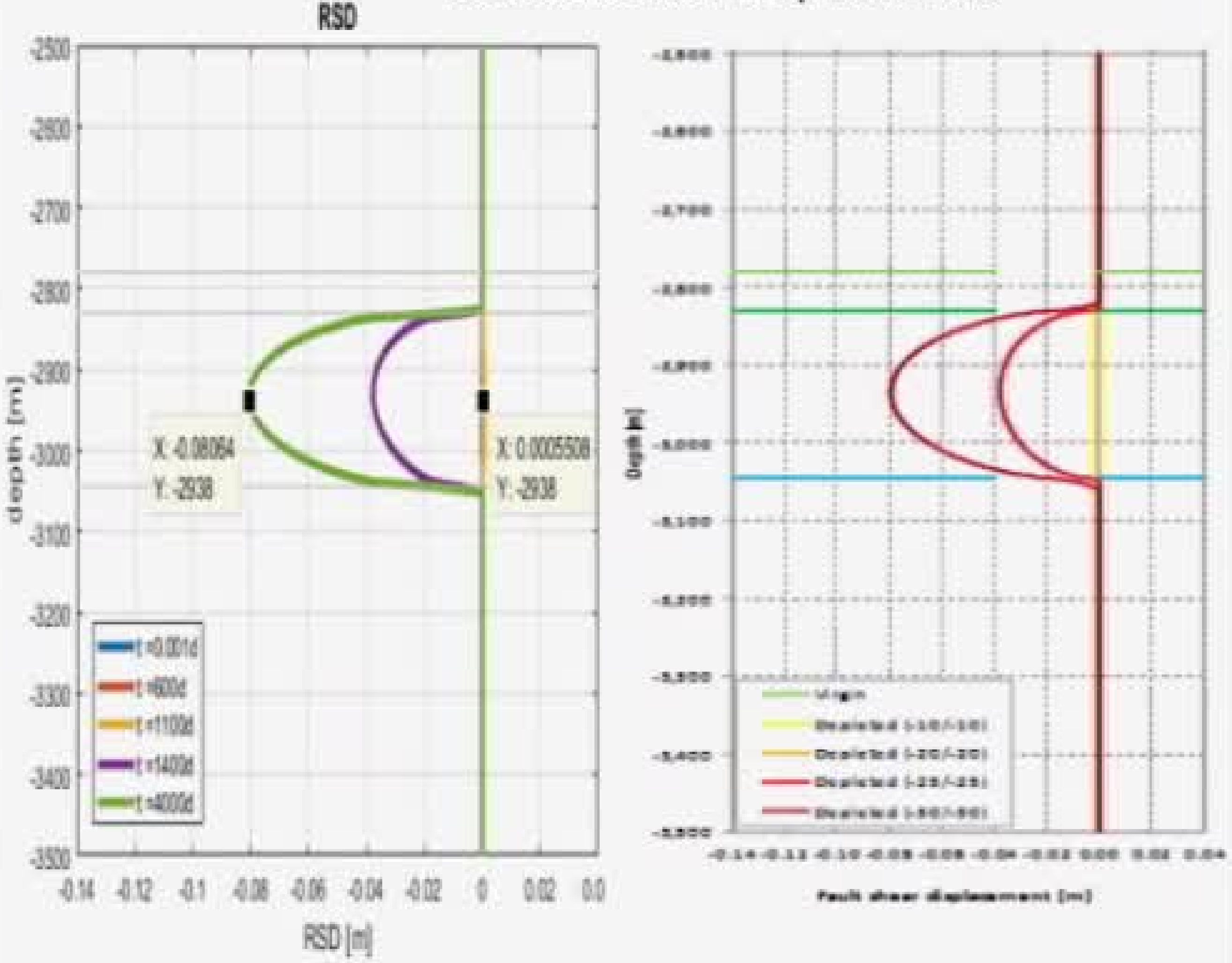
Shear Capacity utilization



ADGPRS result

Reference [10]

Relative Shear Displacement

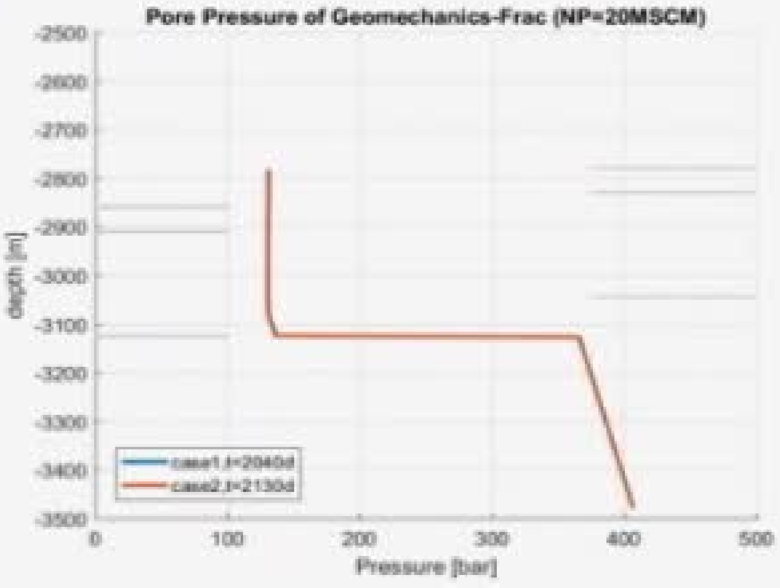


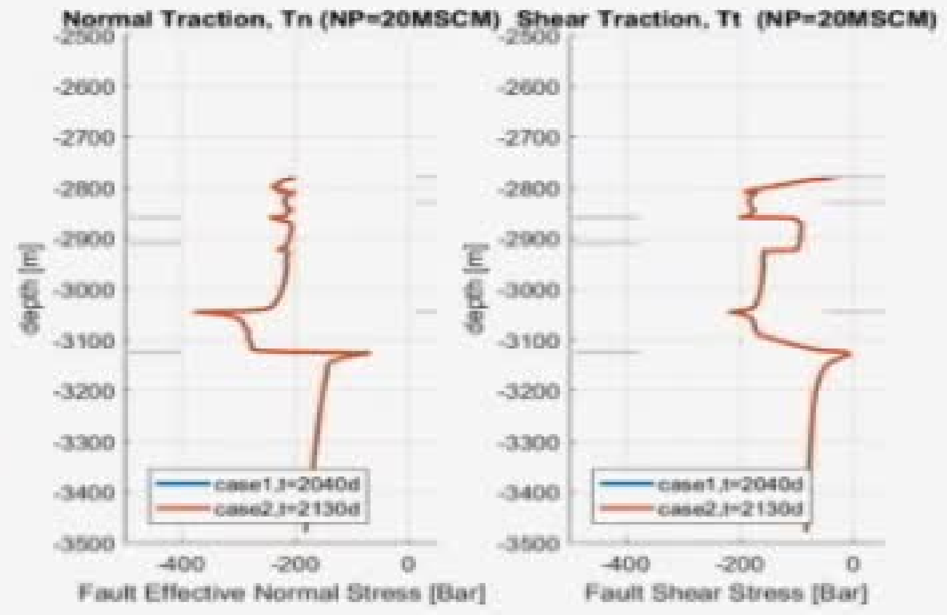
ADGPRS result

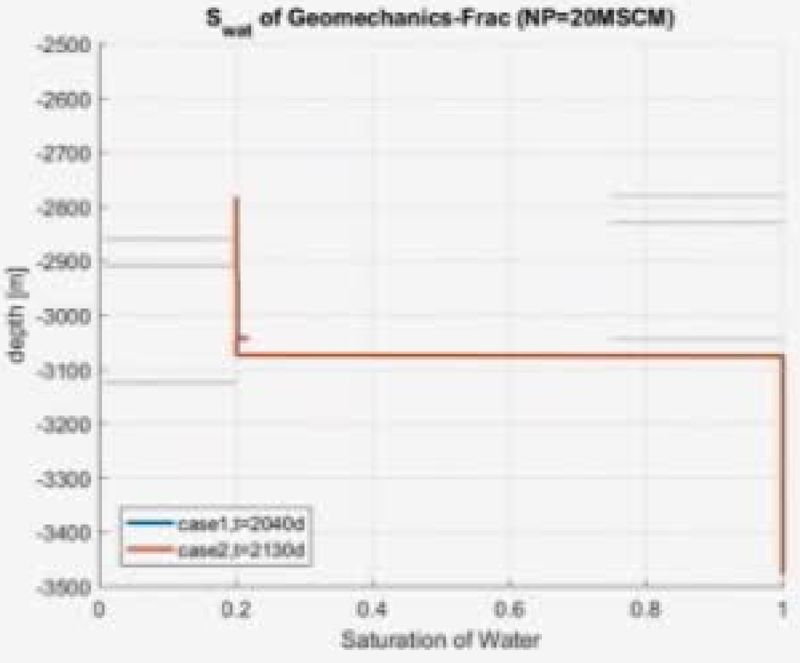
Reference [10]

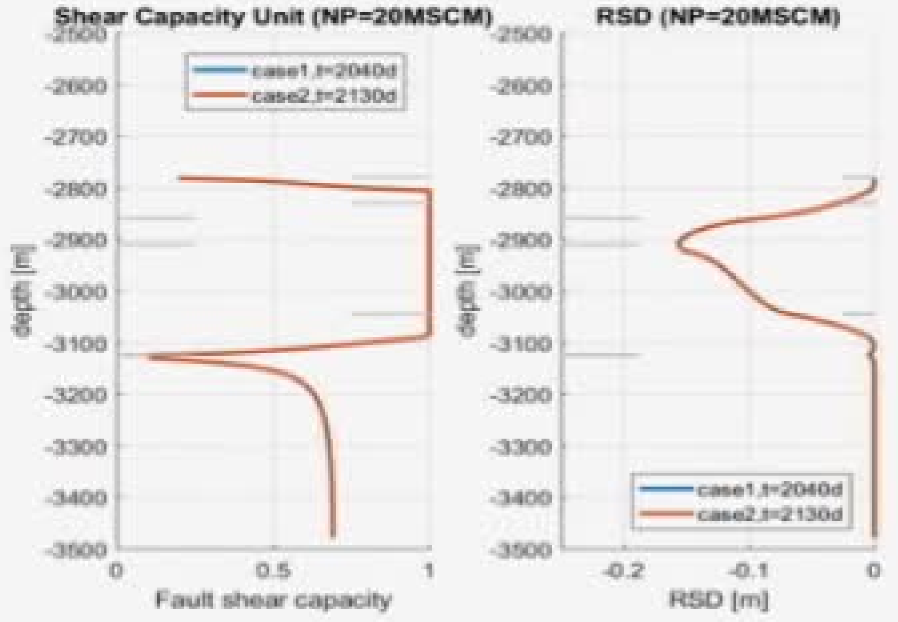
TUDelft

Non-conductive fault





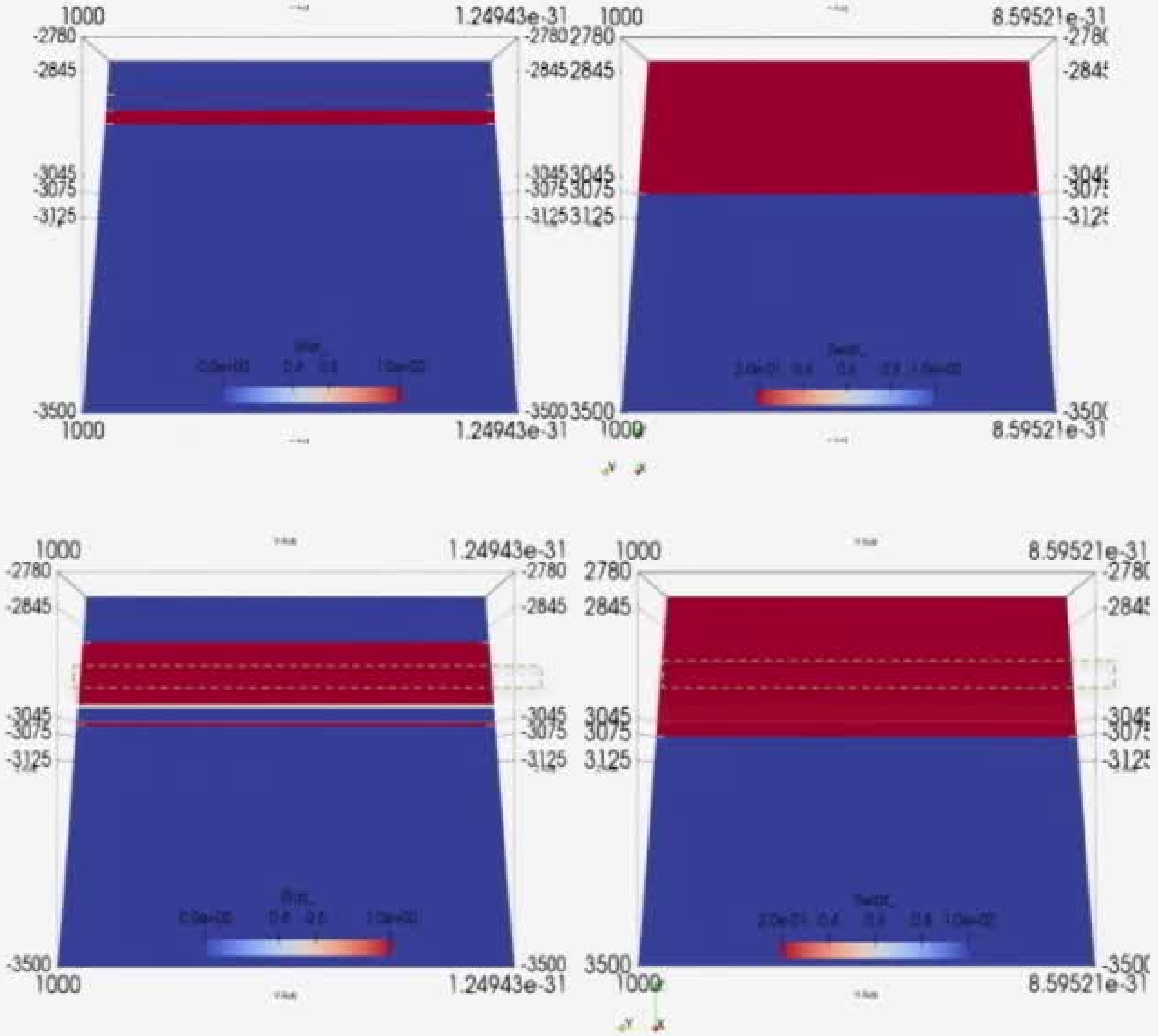




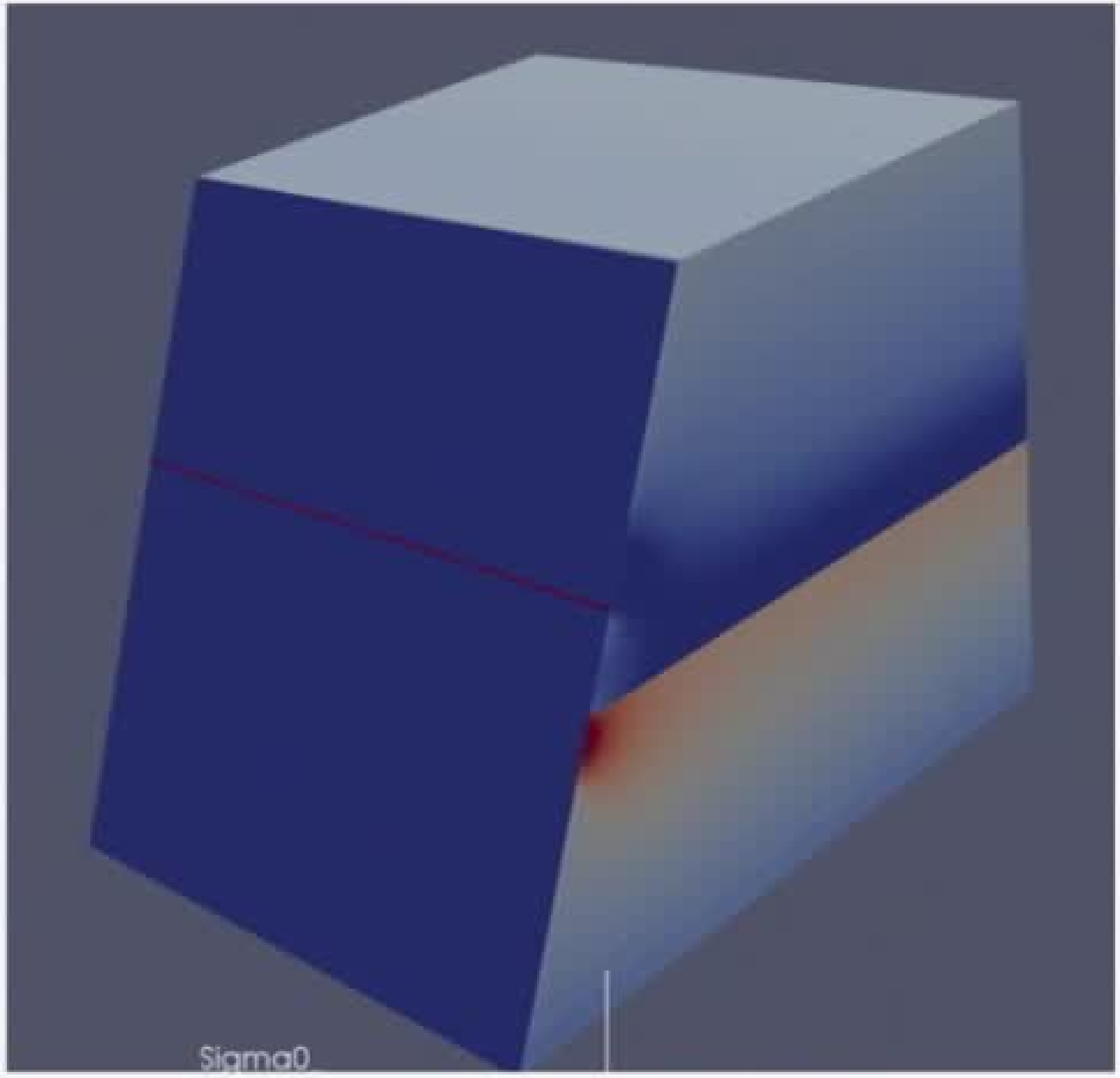
Conductive fault response

- Rocks with low friction is easier to break.
- The failure propagates towards the weaker rock.

- Early failure at depth 3045 mTVD results in water seeping into the fault.

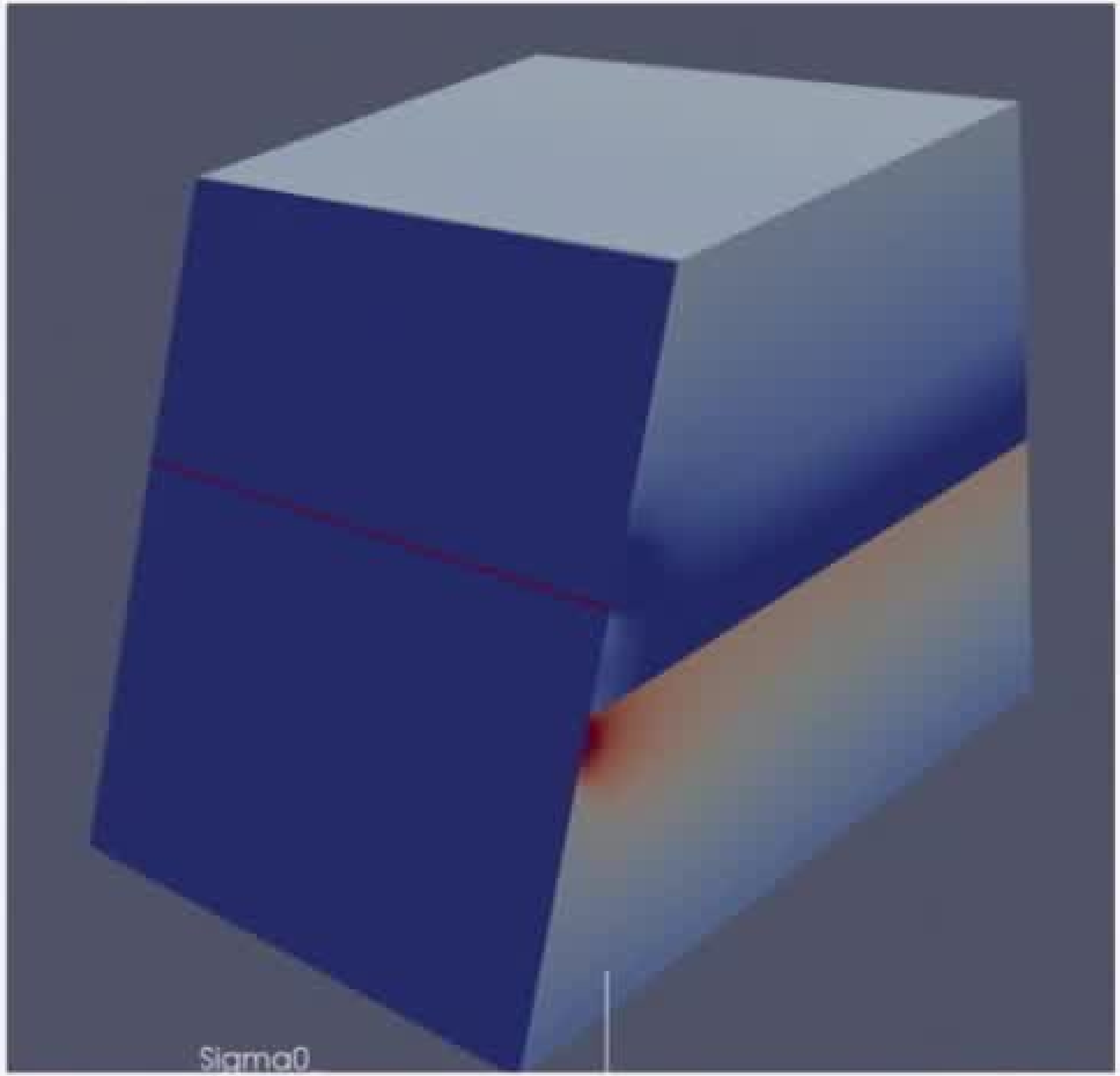


Fault response with dissolution

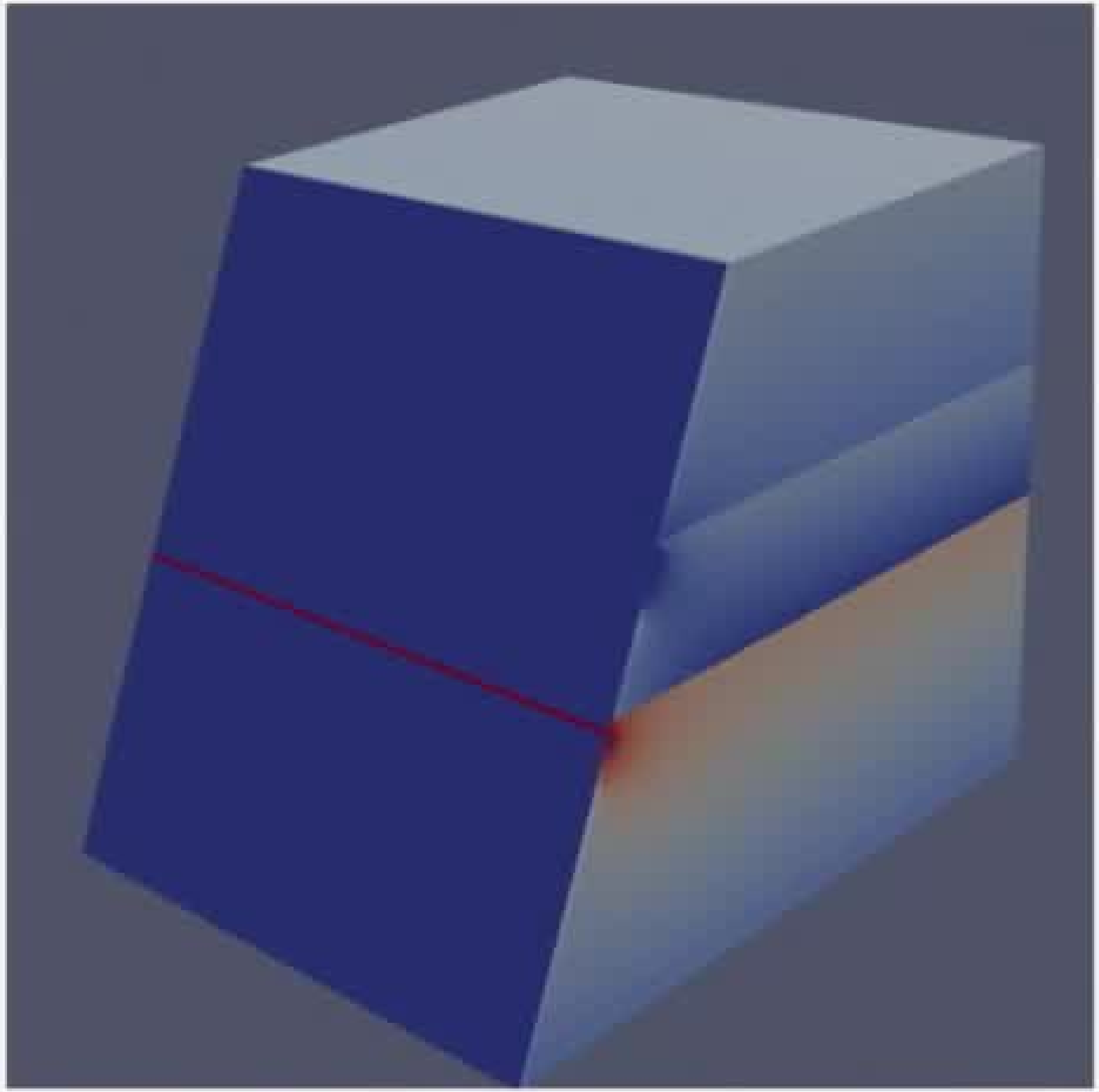


Stress map and failure status after
213 days with constant friction

Fault response with dissolution



Stress map and failure status after 213 days with constant friction



Stress map and failure status after 121 days with alternating friction

Conclusions

- The fault properties depends on chemical interactions with in-situ fluids (brine)
- We developed a simulation platform for coupling of chemical interactions in the fault (or matrix) with mechanical response
- The modeling approach was validated against existing numerical study at NAM
- Sensitivity and uncertainty analysis will be performed and compared against experimental results

Acknowledgements

- Ghina Ihsan
- SUPRI-B at Stanford University

Science4Steer project

1. Characterize the inelastic and hysteretic mechanical compaction and decompaction of sandstone reservoir rock under stress reversals
2. Characterize the frictional response of fault rocks under (multiple) combinations of pore pressure, normal stress and shear stress reversals.
3. Characterize the evolution of microseismicity, mechanical and acoustic properties, and reservoir rock under (multiple) stress reversals.
4. Develop modelling capabilities for laboratory-scale compaction and friction experiments and scaling relationships of (near-)fault response
5. To assess and quantify, through multi-scale numerical simulation up to field (segment)-scale and the effects of temporal and spatial changes in pore pressure in response to production
6. Investigate and quantify the controllability of pressure and deformation states through manipulating injections and production rates in space and time, and to develop methods for robust optimal control of operational variables to minimize induced seismicity