Application of PFC3D in earthquake modelling and seismic hazard assessment of an underground nuclear waste repository

Jeoung Seok Yoon (jsyoon@gfz-potsdam.de), DynaFrax UG

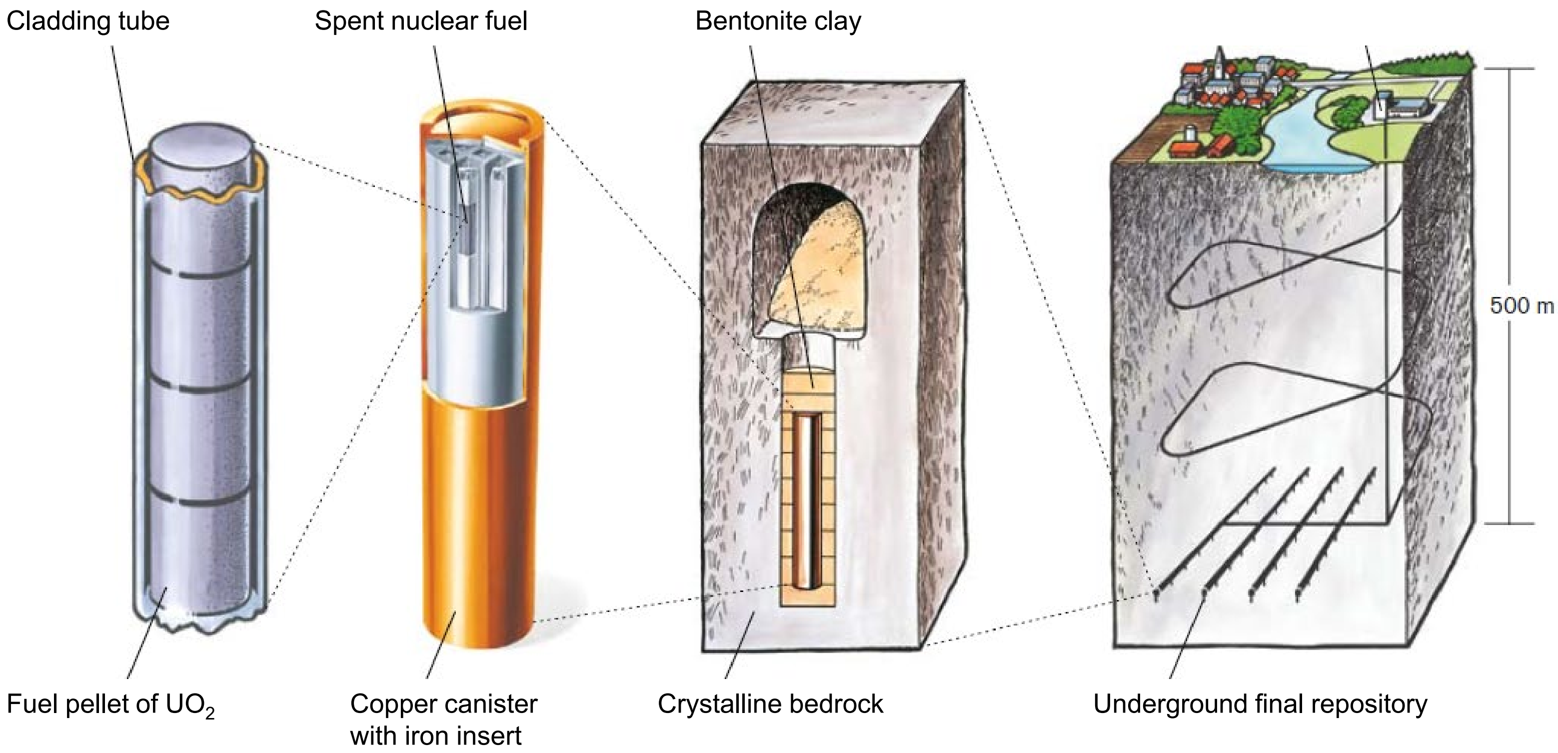
Arno Zang & Ove Stphansson, GFZ

Carl-Henrik Pettersson, SSM

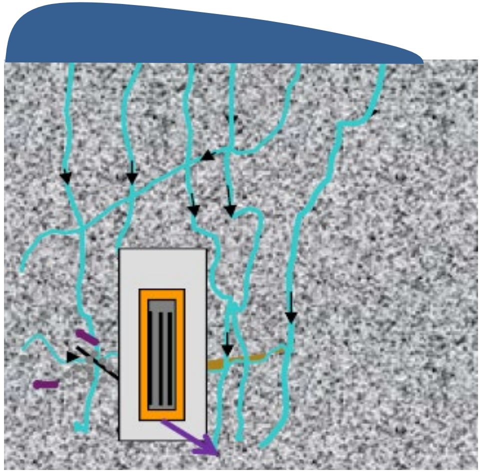
Flavio Lanaro, GEOSIGMA

DynaFrax Experts in Dynamics of Rock Fractures for GeoCoupledProcess Modelling and GeoHazardRisk Analysis

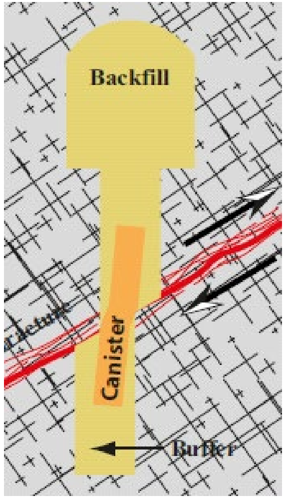
KBS-3V concept for disposal of spent nuclear fuel



Three possible modes of failure of copper canister



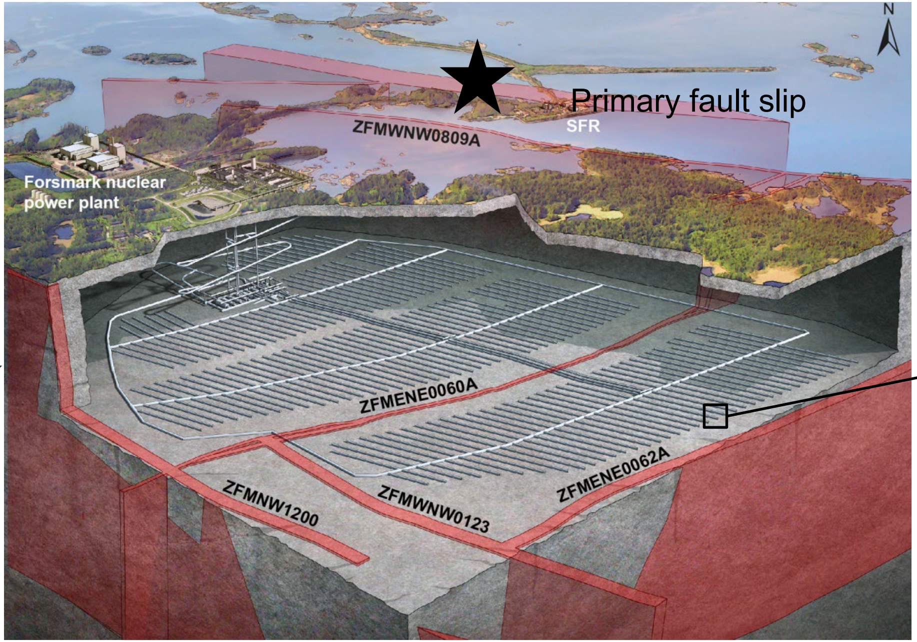
Main scenario



Less likely scenario

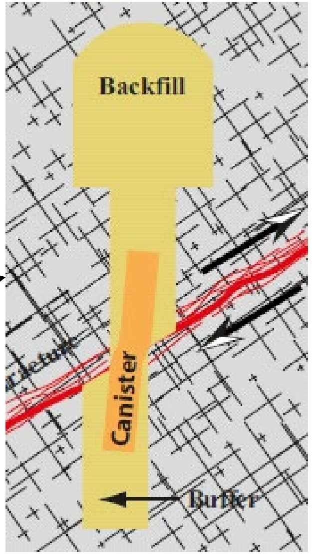
Very unlikely scenario

Forsmark repository for final disposal of spent nuclear fuel



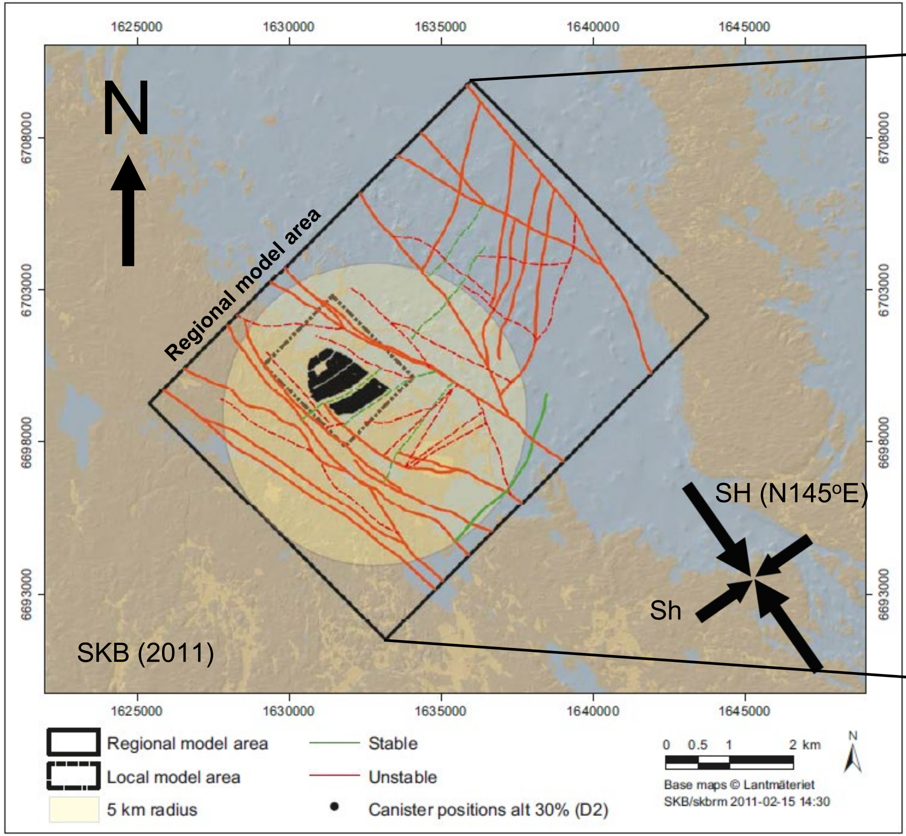
Modified from SKB (2011) and Yoon et al. (in prep.)

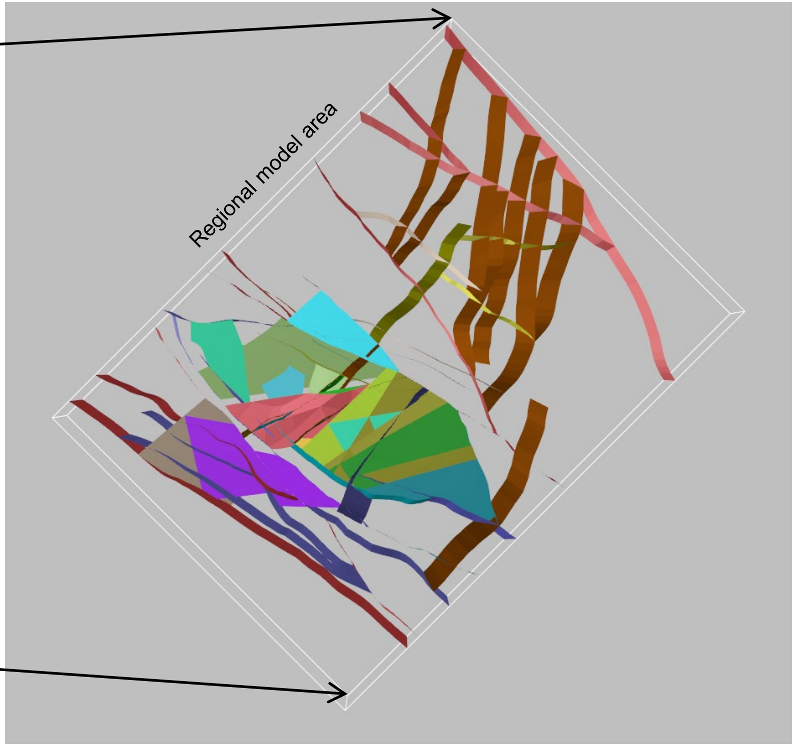
Secondary fracture slip



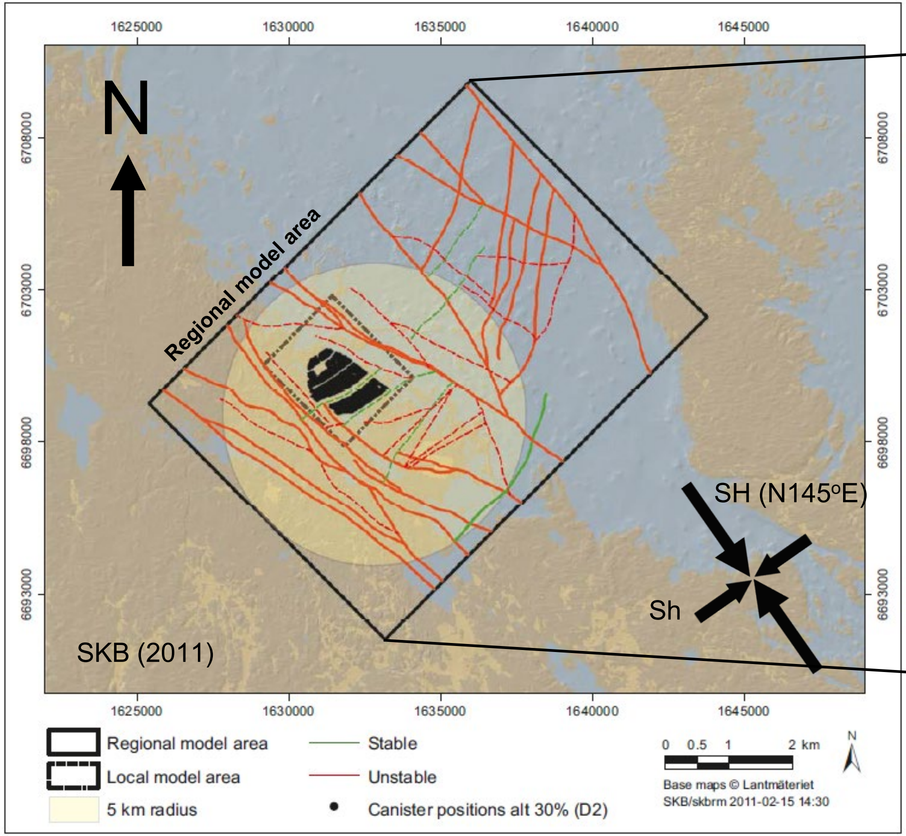
Fälth et al. (2010)

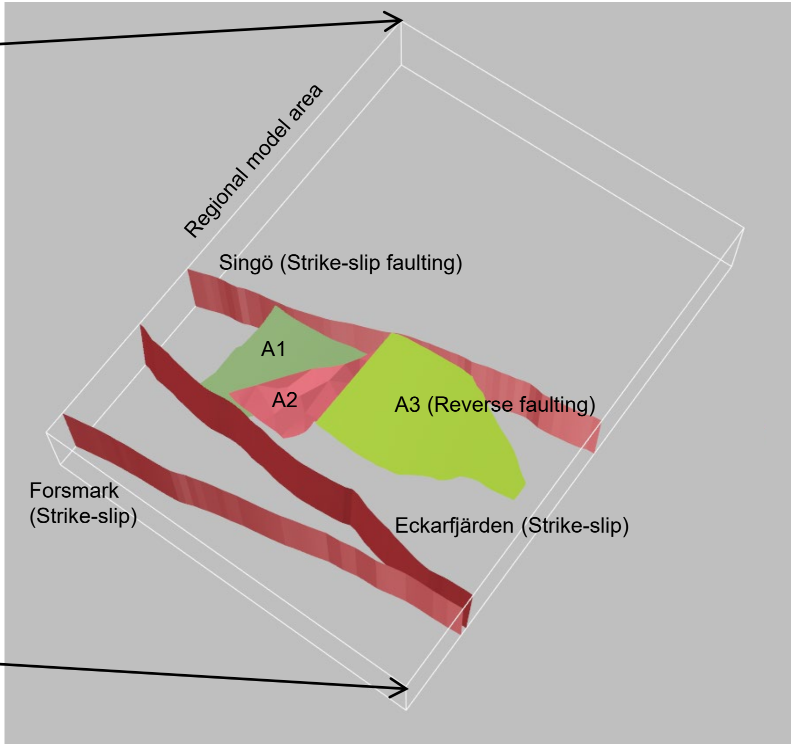
Major deformation zones



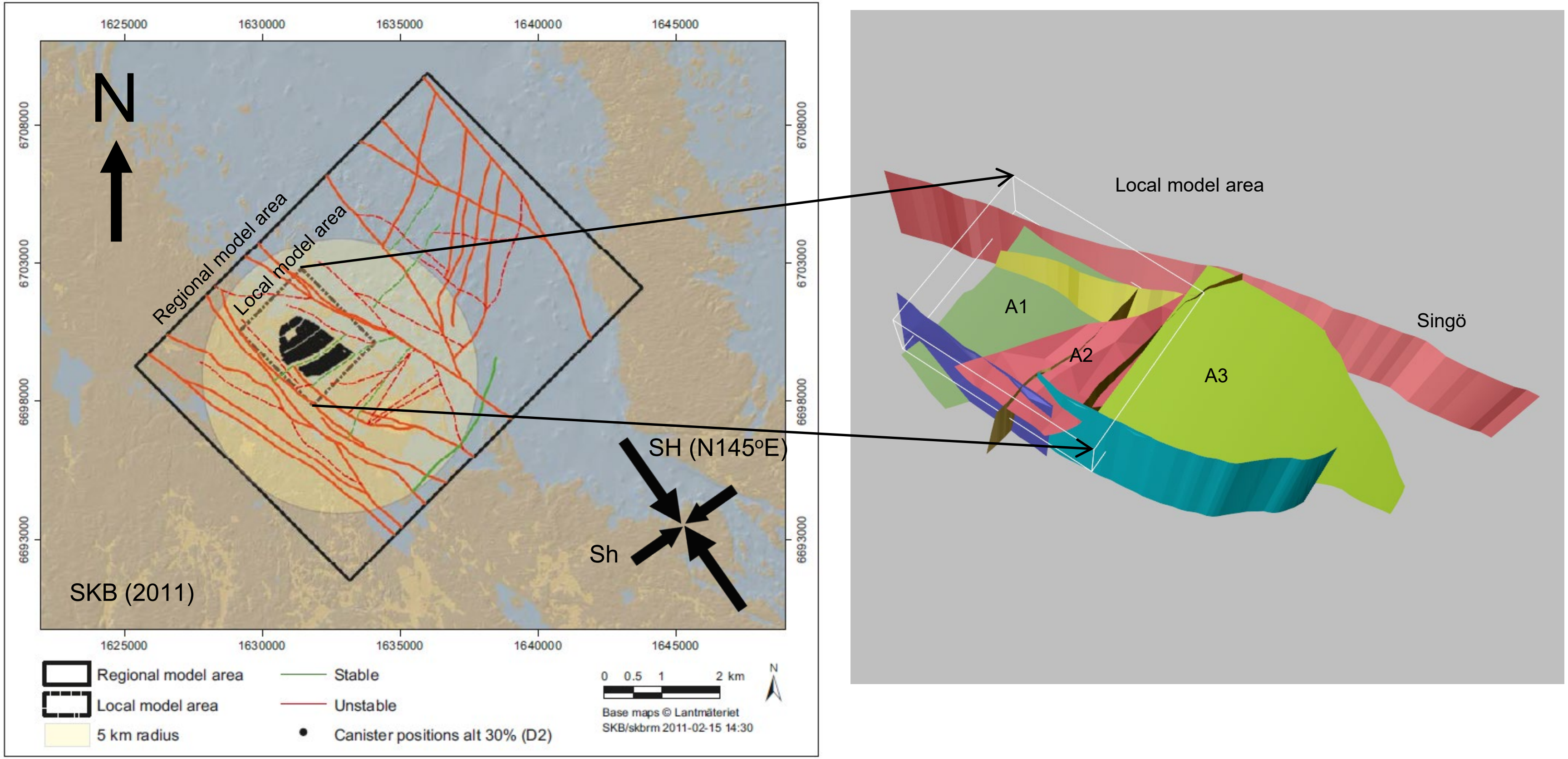


Major deformation zones





Major deformation zones

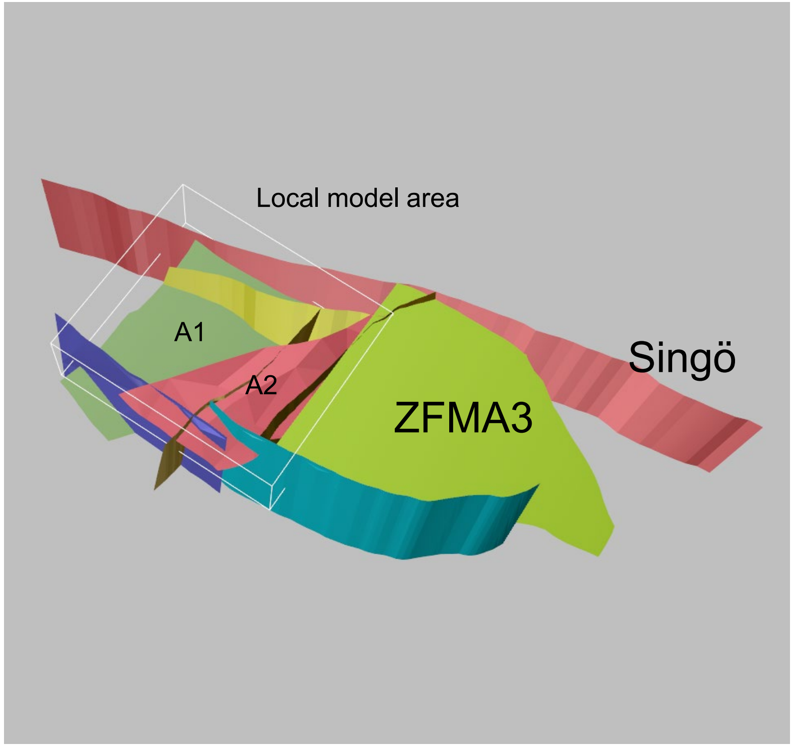


Major deformation zones

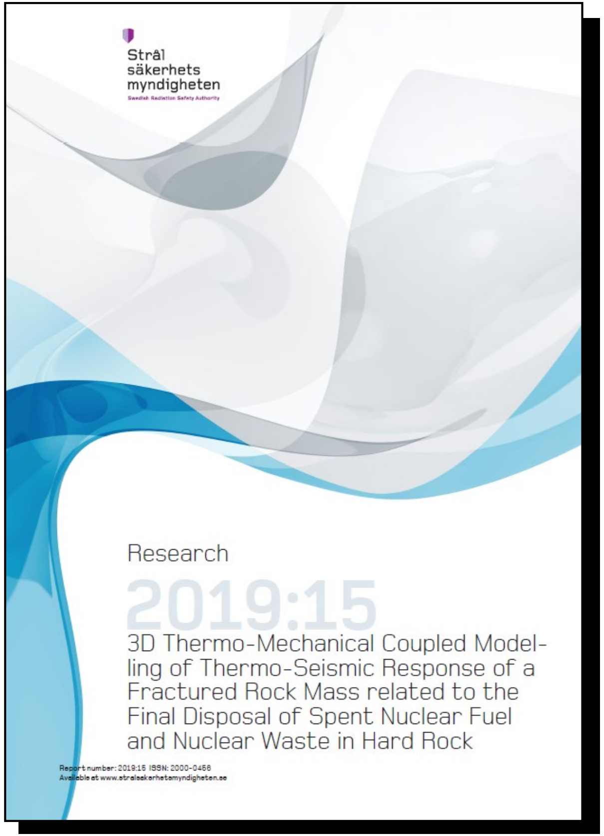
Deformat-ion zone	Dip (deg)	Area (km^2)	Moment magnitude*
Singö	90	55	5.5 ~ 6.1
ZFMA3	16	31	5.3 ~ 6.0

$$M_w = \frac{2}{3}\log(GAd) - 6$$

* assuming, d = 0.1 ~ 1 (m)

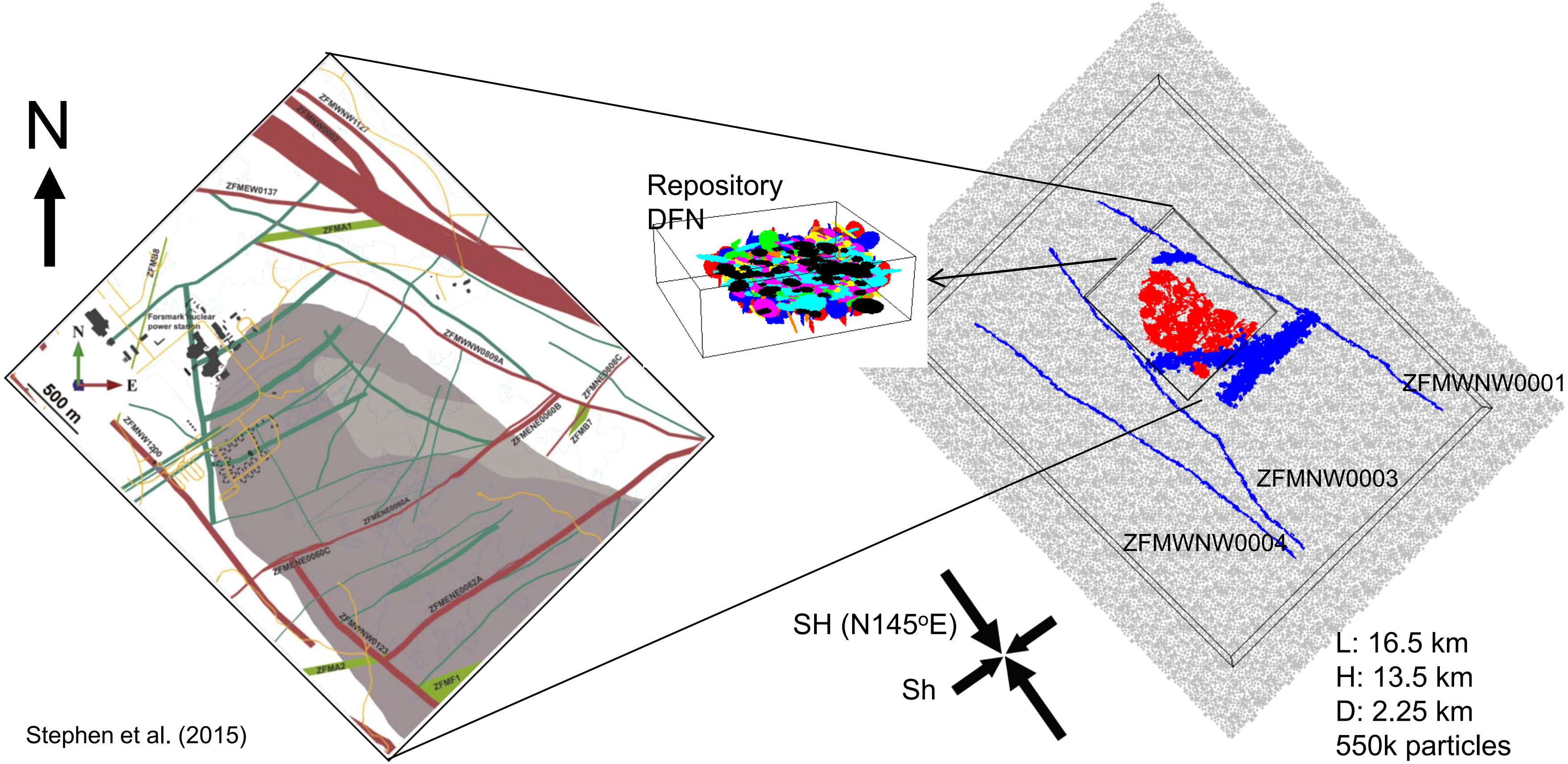


Objectives of the modelling study (Yoon & Zang, 2019)



- Develop a 3D model of Forsmark site geology and repositoy rock mass, using PFC3D
- Develop a dynamic modelling technique for simulation of an earthquake event, fault dynamic rupture, and seismic source validation
- Investigate secondary slip of the repository fractures by the effect of earthquake event
- Develop a thermo-mechanical coupled modelling technique for simulation of heat transfer in rock mass
- Investigate thermally induced slip of the repository fractures

PFC3D model for Forsmark site geology

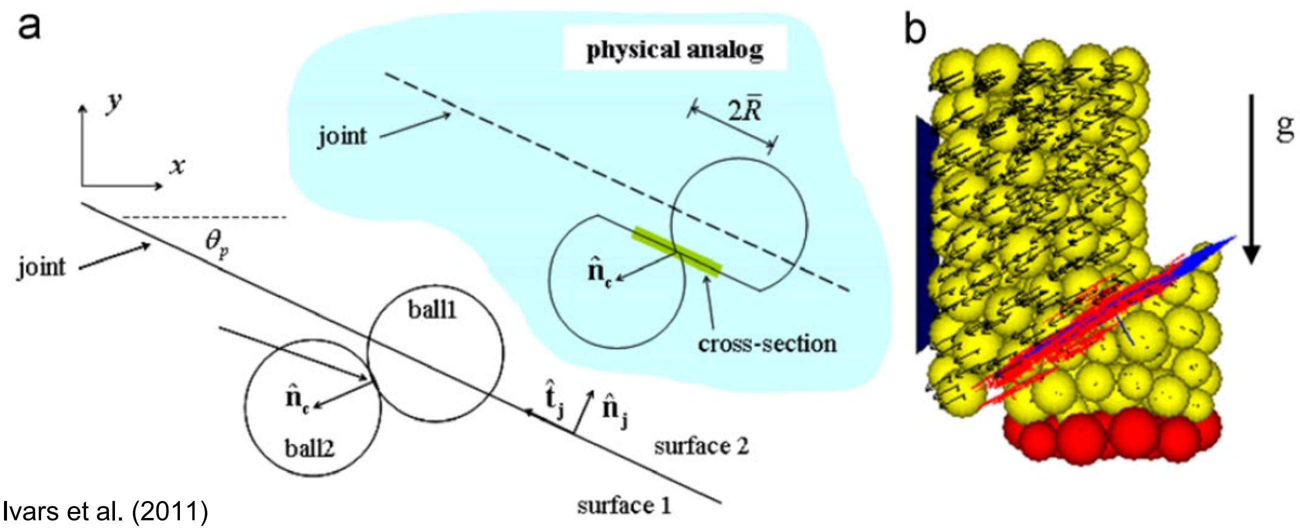


Stephen et al. (2015)

Yoon & Zang (2019

L: 16.5 km
H: 13.5 km
D: 2.25 km
550k particles
(using AC/DC)

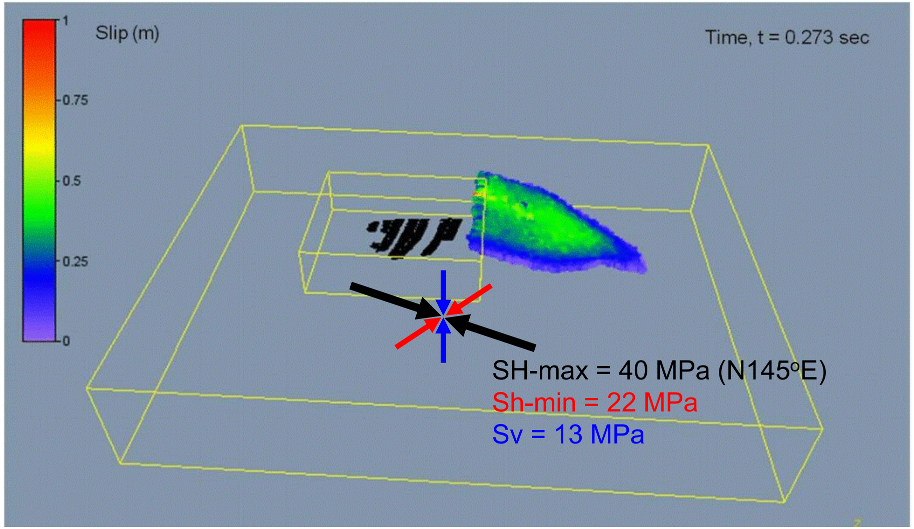
Fracture representation by smooth joint contact model

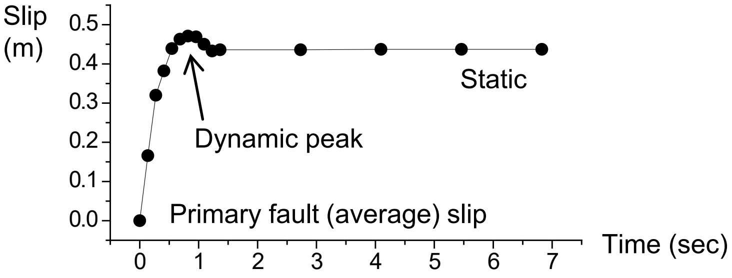


Mas Ivars et al. (2011)

Planar disk joint → Collection of smooth joint contacts

Simulation of an earthquake event (fault dynamic rupture)





Lock the seismogenic fault plane

Power-up the smooth joint contact strength and stiffness

In situ stressing

Present day reverse faulting stress field

Unlock the fault plane

Force-down the strength and stiffness (asperity lost by rupturing), initiate rupture & generate seismic wave

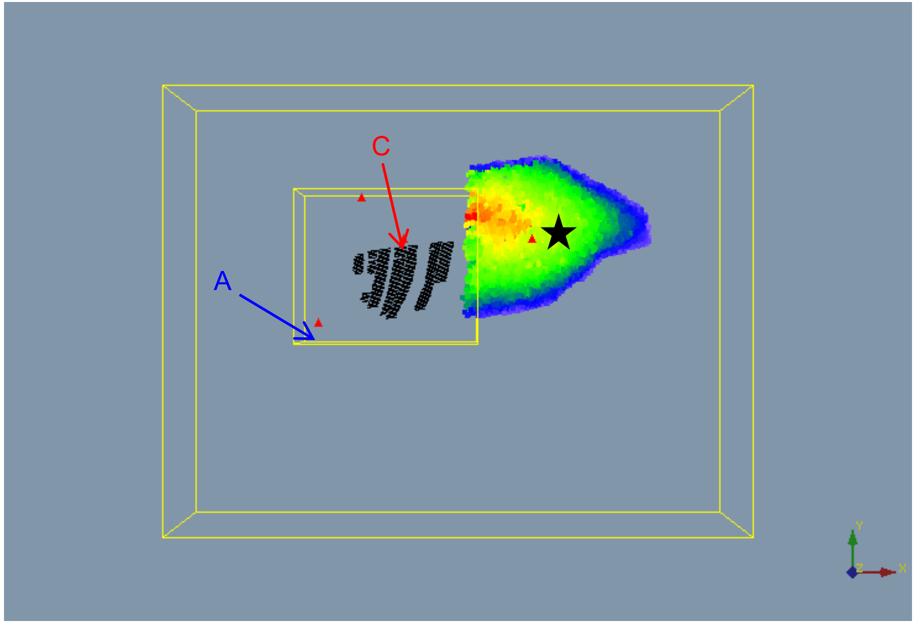
Example) ZFMA3 activation

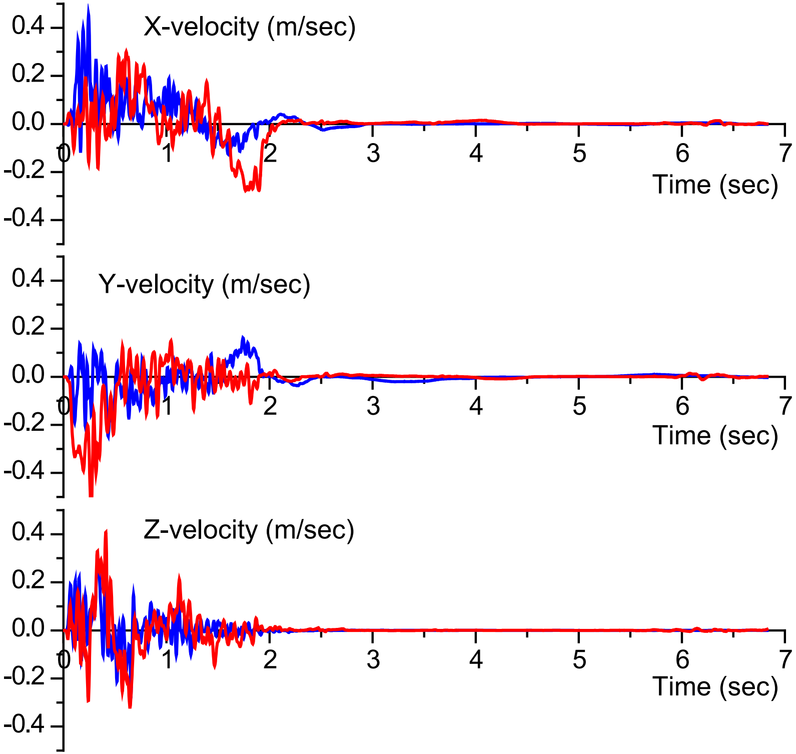
Average slip displacement, d = 0.42 m

Moment magnitude, Mw = 5.7

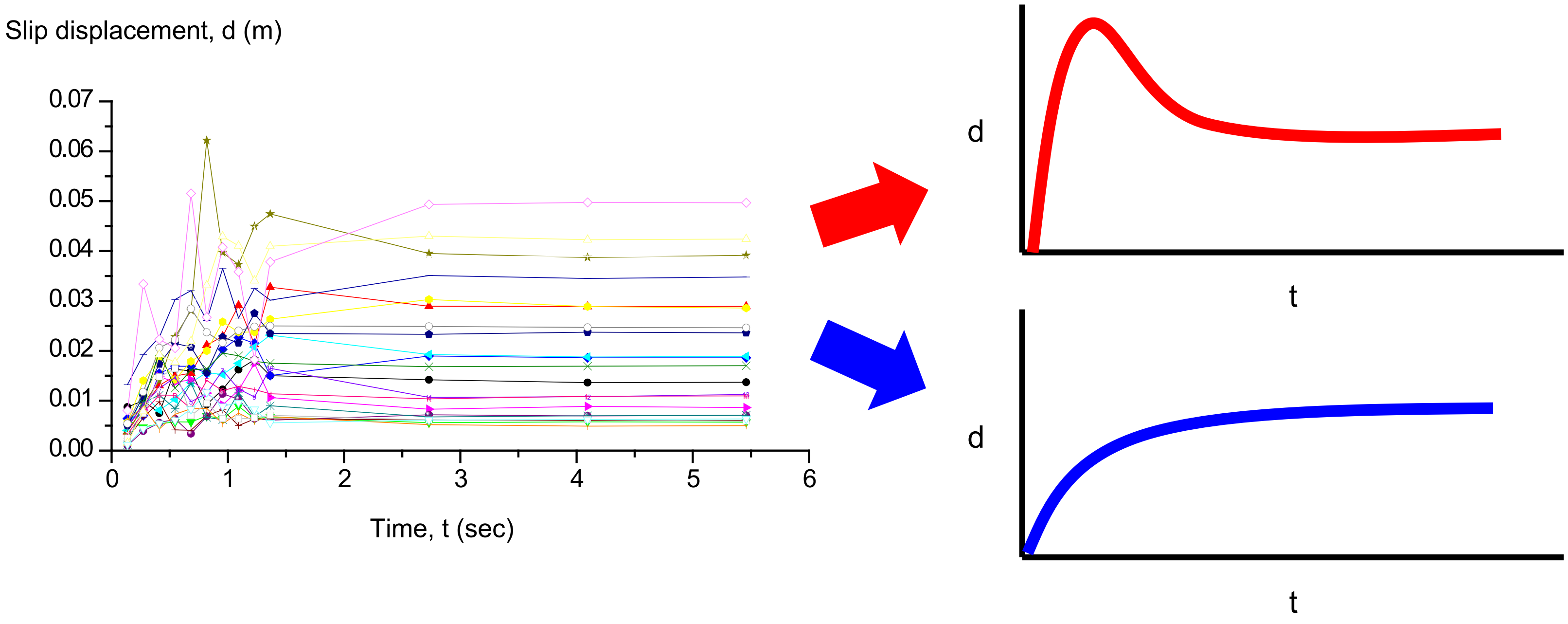
$$M_w = \frac{2}{3}\log(GAd) - 6$$

Seismic wave propagation and attenuation

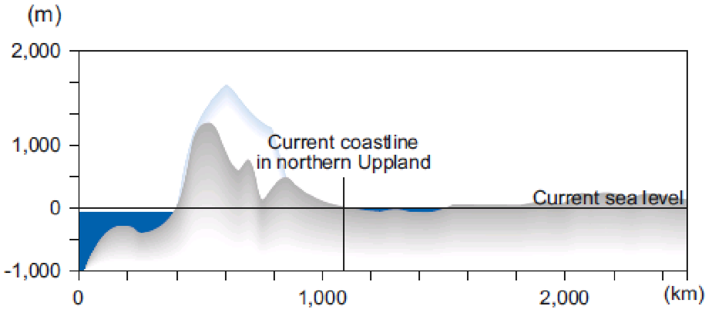




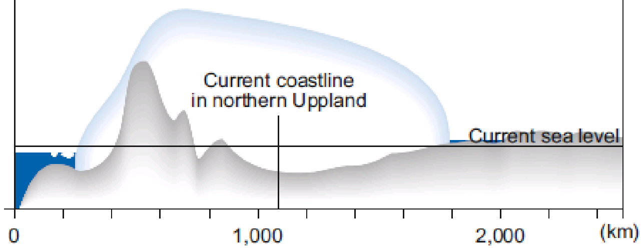
Secondary slip development of the repository fractures



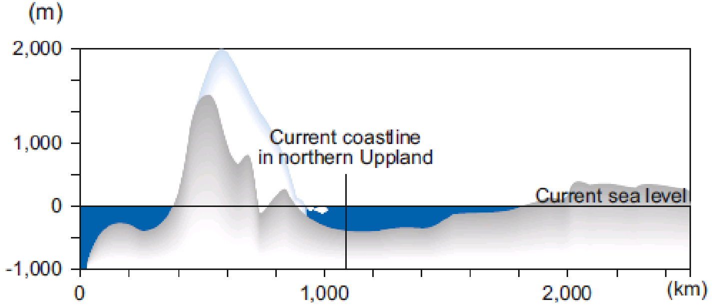
Effect of glaciation: Weichselian ice sheet



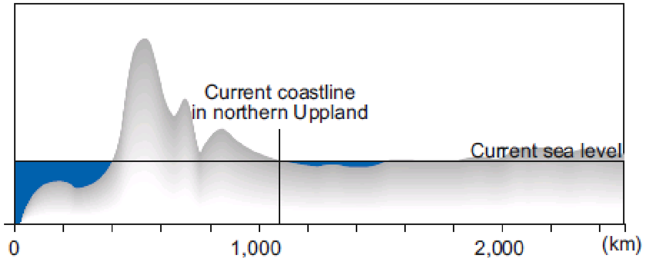
Cold climate & ice sheet expands
Permafrost



Maximum ice sheet & rock stress increase



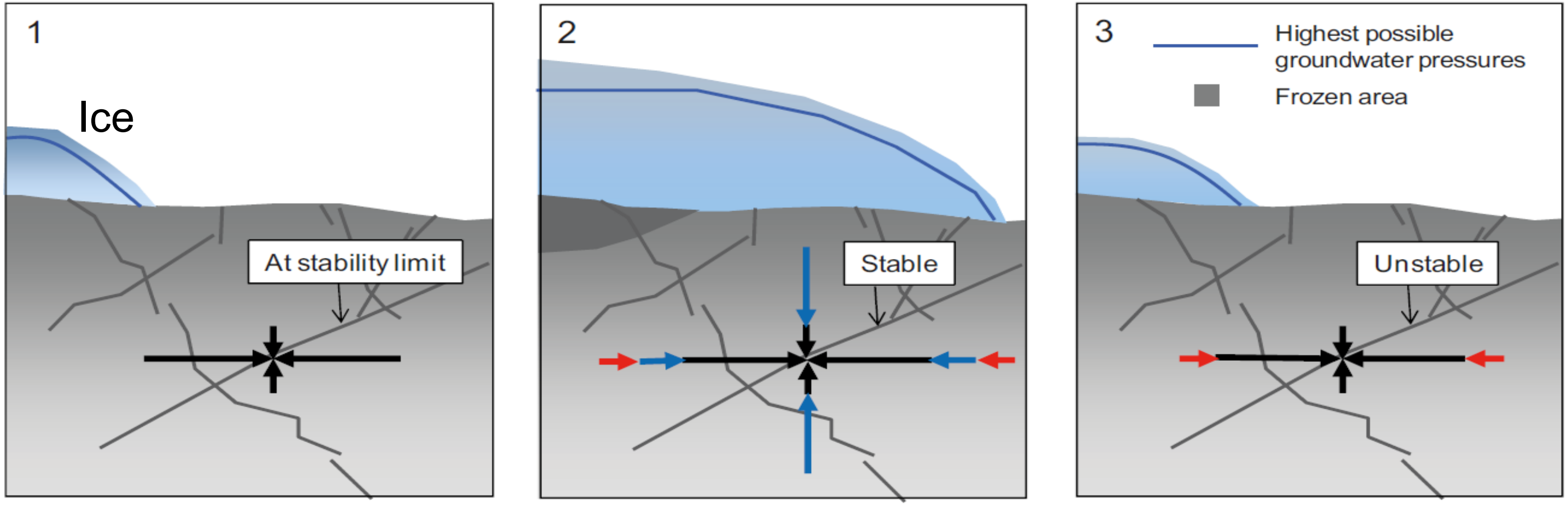
Warmer climate & ice sheet retreat Bedrock instability.



Warmer climate & slow rebound
Post-glacial earthquakes

SKB (2011)

Bedrock instability with ice sheet retreat



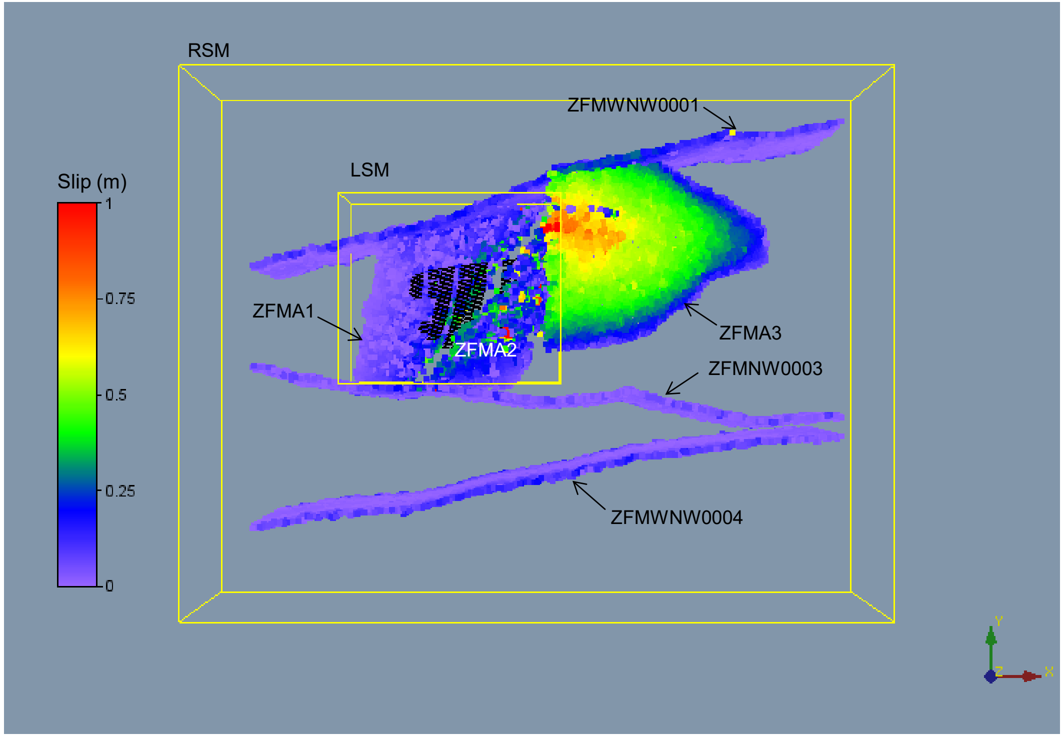
Present day anisotropic stress field

Stress field under stabilizing ice cover

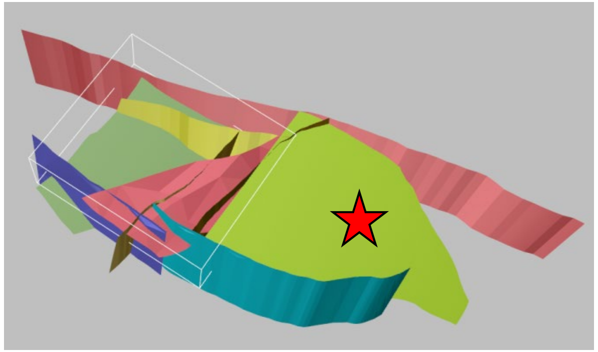
Stress field under retreating ice cover, Fault instability!

Fälth et al. (2010)

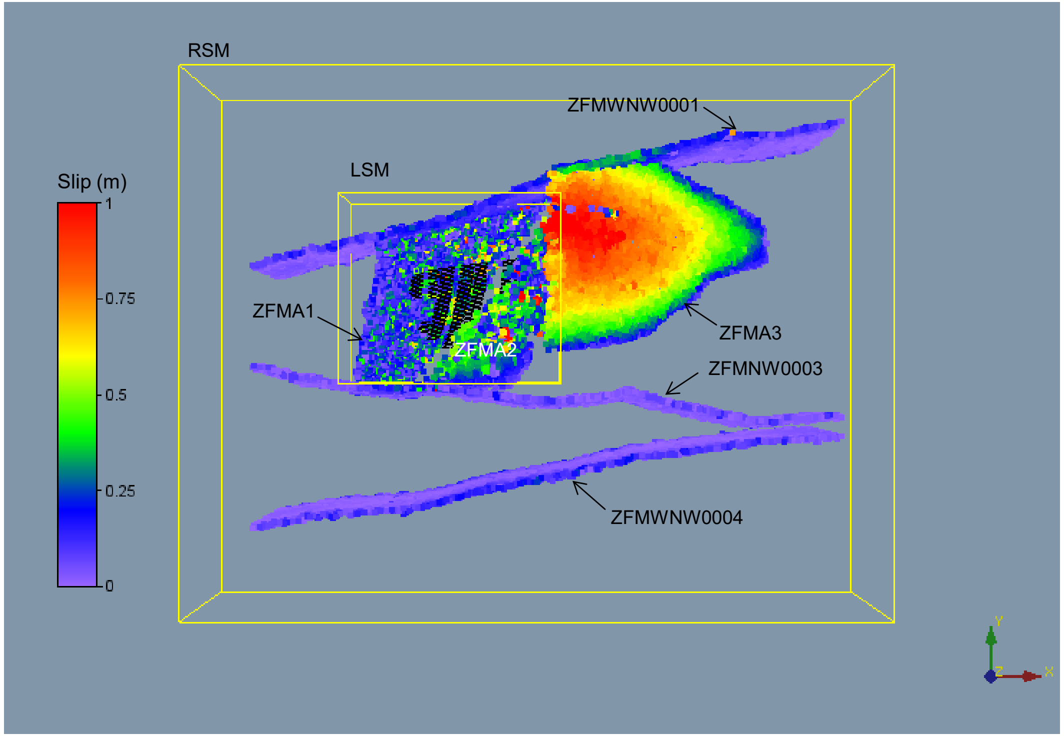
Activation of ZFMA3 under present day stress condition



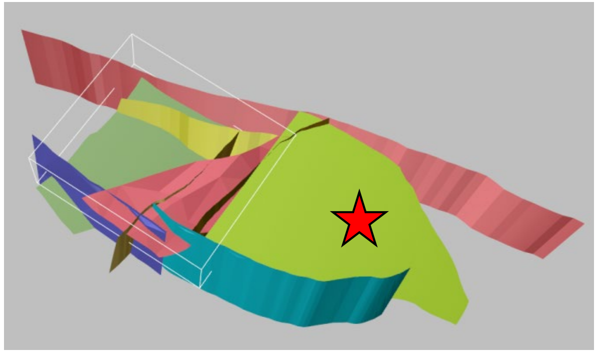
ZFMA3 (reverse faulting)
- Length = 4,900 m
- Slip = 0.42 m
- Mw = 5.7



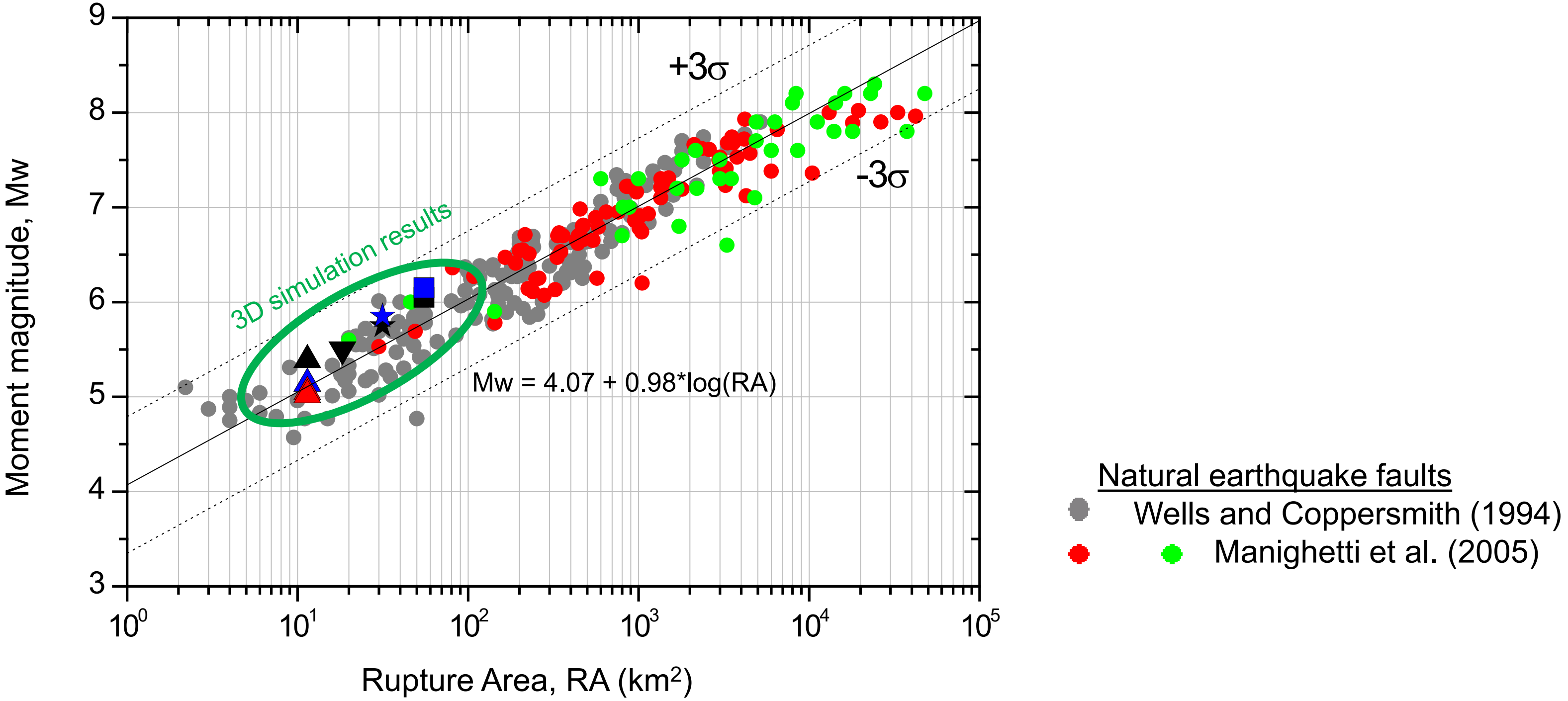
Activation of ZFMA3 under ice sheet retreat stress condition



ZFMA3 (reverse faulting)
- Length = 4,900 m
- Slip = 0.63 m
- Mw = 5.9

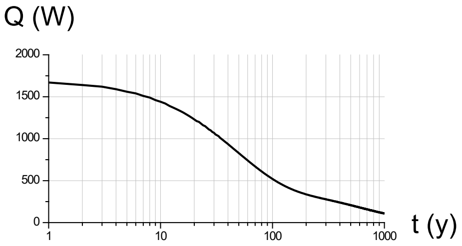


Comparison to natural tectonic earthquake fault data

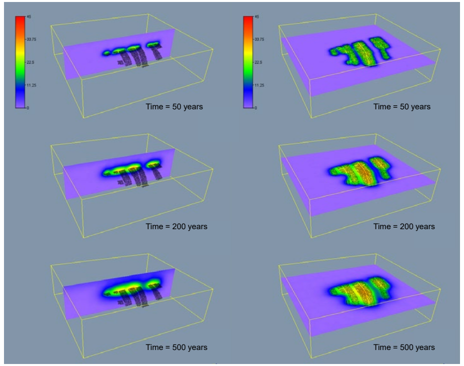


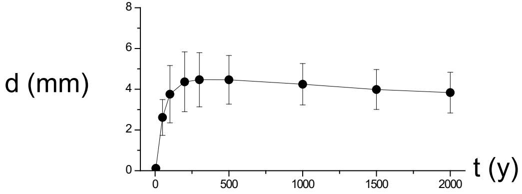
Summary

- Using PFC3D, we developed a 3D geological model of the Forsmark repository site including major deformationzones and the repository fracture network.
- A numerical modelling technique for simulation of an earthquake event is developed, and confirmed the validity of the simulated seismic source parameter by comparing to natural tectonic earthquake fault data.
- A few scenarios of earthquake events occurring at one major deformation zone (ZFMA3) at Forsmark repository site are simulated. The simulated event has Mw 5.7, with mean slip displacement of 0.4 m, and shows good match with worldwide natural tectonic earthquake fault data.
- The secondary slip of the repository fractures shows two type of temporal development behaviors, and a few fractures slip > 5 cm, but needs further study (Performance Assessment) to relate the results to canister damage.
- 3D thermo-mechanical coupled modelling is presented in SSM report 2019:15 (Yoon & Zang, 2019).

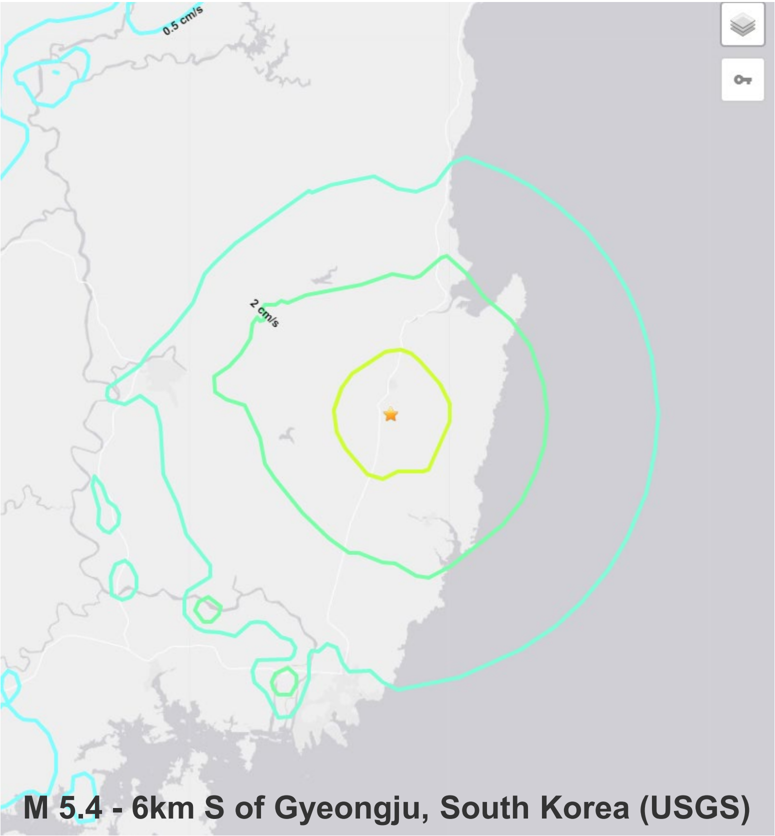


ΔT (ºC) distribution





A quick & dirty example in 2D



M 5.4 - 6km S of Gyeongju, South Korea (USGS)