Forsmark Site Visit

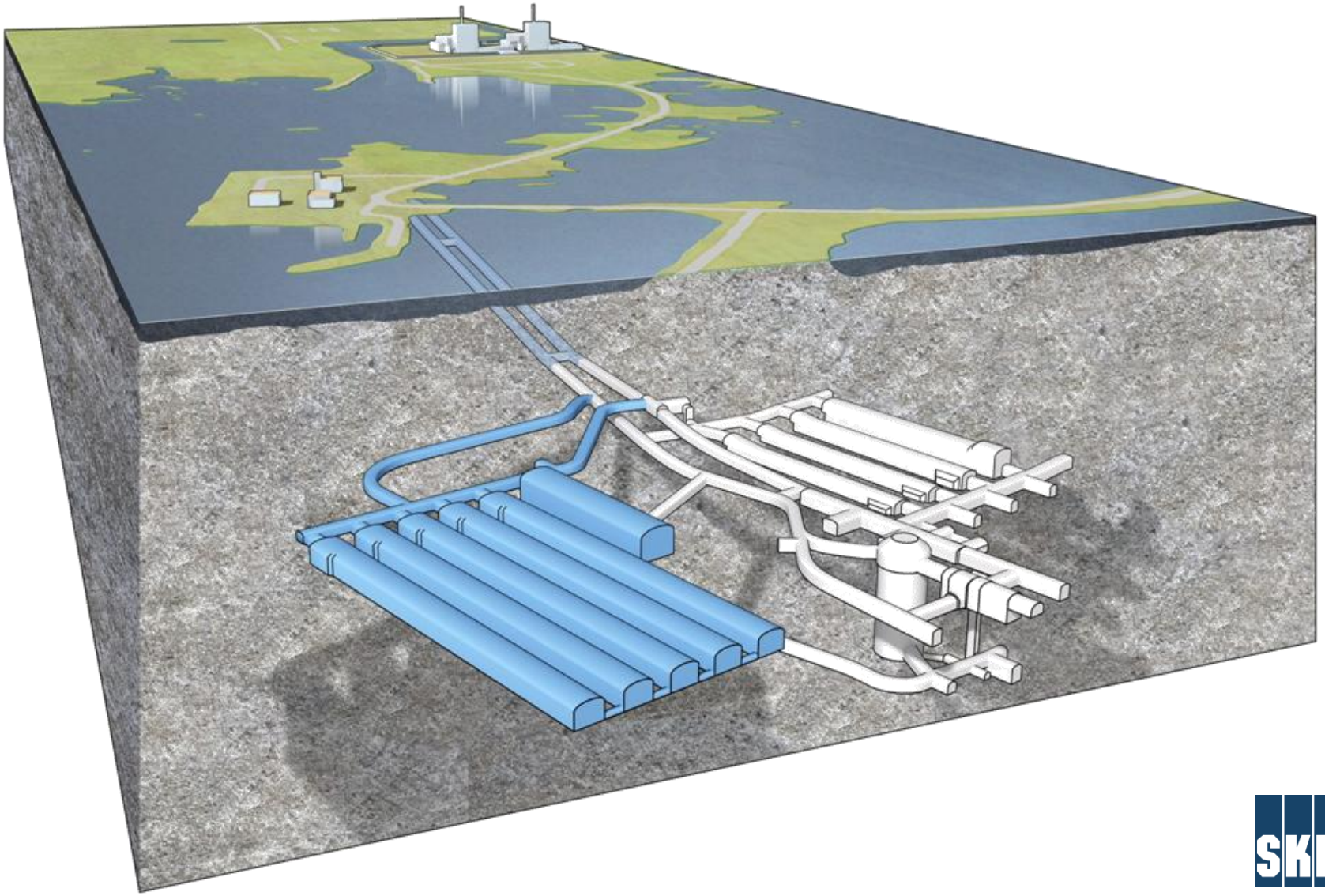
Topics for discussion:

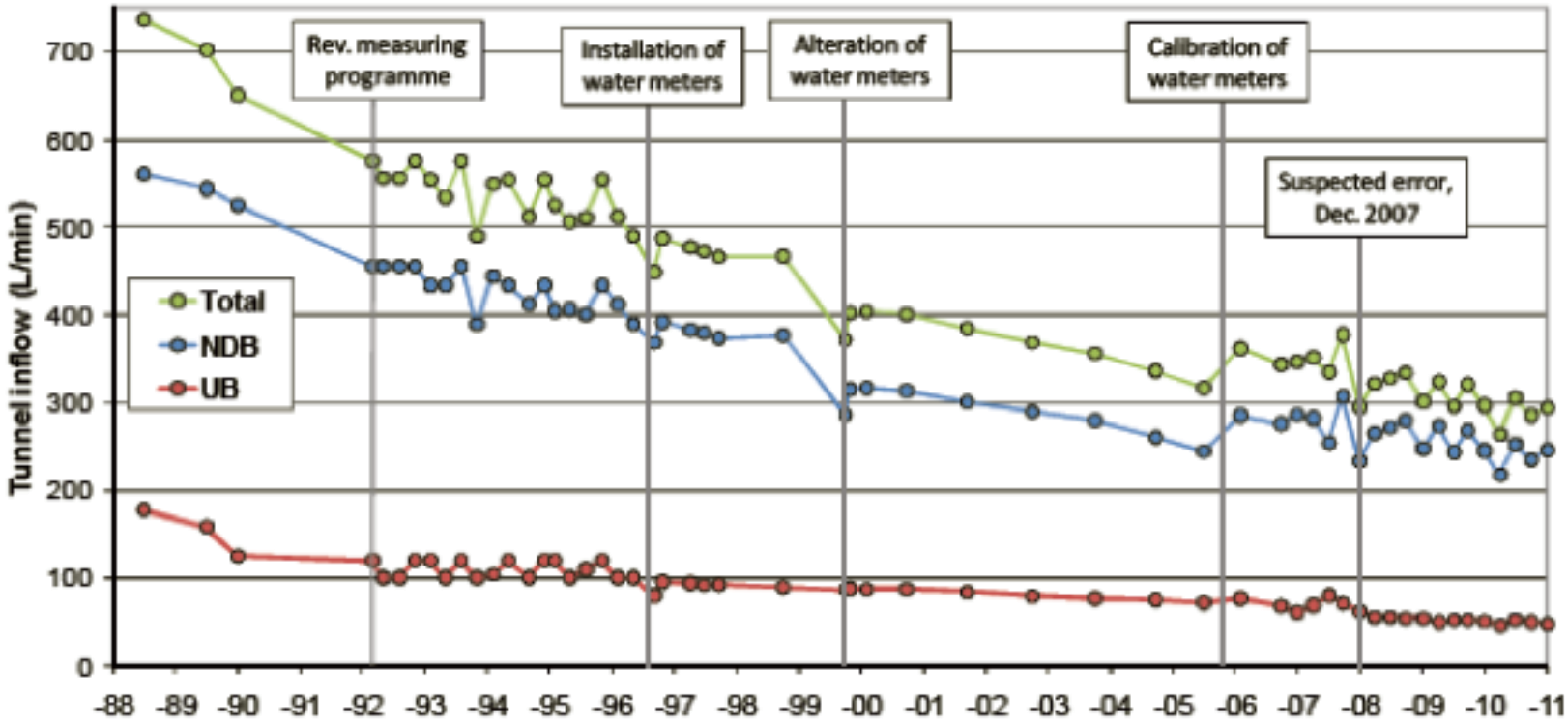
1. Future changes in hydraulic fracture properties
2. Data supporting transmissivity of reactivated fractures

Observed changes in hydraulic conditions occurring today at our underground facilities

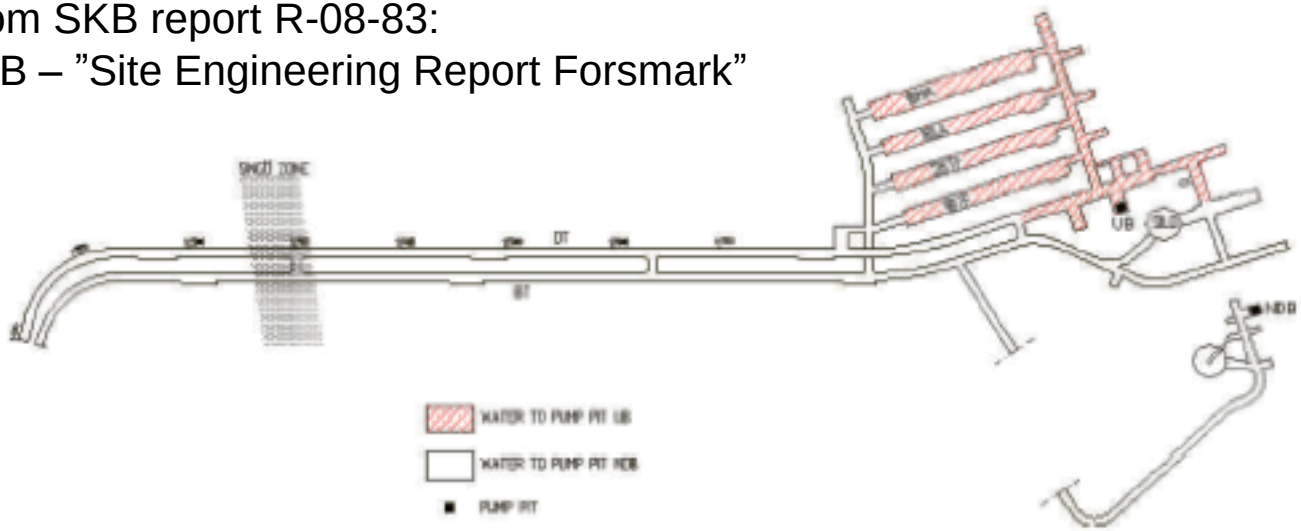
- SKB Operates 3 underground facilities:
  - Äspö (~450 m depth)
  - SFR (~60 to 100 m depth
  - Clab (~40 m depth)
- At all Facilities the inflows are significantly decreasing with time
- While this is observed we do not factor this reduction into the Safety case. We simply assume that upon closure the hydraulic properties will return to their pre-excavation state.

SFR Facility (White) Planned extension (Blue)





From SKB report R-08-83:
SKB – ”Site Engineering Report Forsmark”



SFR Facility

Forsmark Site Visit

Topics for discussion:

1. Future changes in hydraulic fracture properties
2. Data supporting transmissivity of reactivated fractures

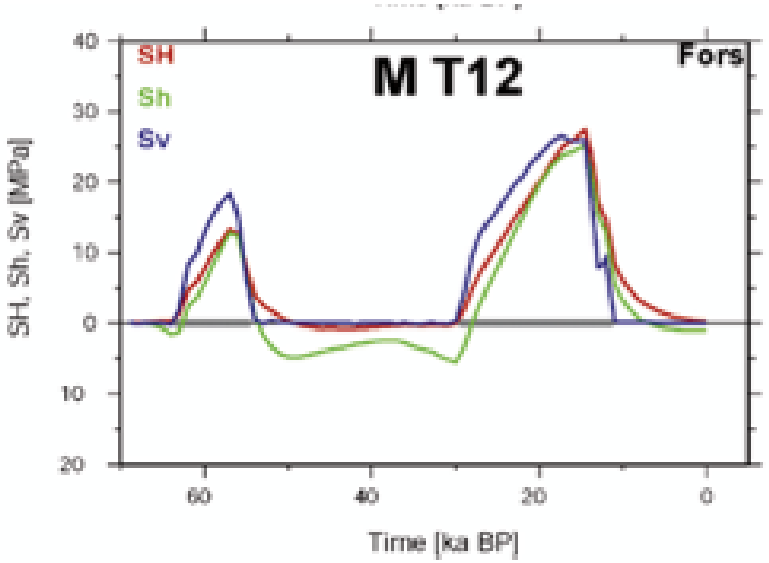
Evidence that site is undergoing detrimental changes due to previous geological loading/unloading

The current site has underground various loading and unloading events throughout geological history:

1) Removal approximately 2 kms of sedimentary rocks
   $\Delta\sigma_{vertical}$=2000 m x 0.026 MPa/m
   $\Delta\sigma_{vertical}$=52 MPa

2) Glacial loading and unloading ~2 kms of ice several times over past 150,000 years

Lund, et al Technical Report TR-09-15 Stress evolution and fault stability during the Weichselian glacial cycle



Evidence for non-mineralised (recent) fractures?

SKB report R-11-02 : Claesson et al ”Assessment of fractures classified as non-mineralised in the Sicada database”

•This study reports the findings from the examination of a group of fractures lacking visible mineralization, i.e. fractures classified as non-mineralised in Sicada, in drill cores from the Forsmark and Laxemar site investigation.

•Non-mineralised fractures may have formed recently, and hence their presence may have implications on site suitability for a deep repository since it could imply that fracturing is an ongoing process in rocks which are considered typical of the Scandinavian shield.

Table 4-1. Total occurrence of non-mineralised fractures at Forsmark and Laxemar. Non-mineralised fractures refer to fractures where Min1, Min2, Min3 and Min4 have no registered entries or where the X5 or X7 codes have been used in the table p_fract_core_eshi. X-codes are used during the core logging when properties or minerals are not represented in the available mineral list.

	All logged fractures	Non-mineralised fractures	% non-mineralised fractures/ all logged fractures
Forsmark	86,268	4,872	5.6
Laxemar	108,263	2,245	2.1
Total	194,531	7,117	3.7

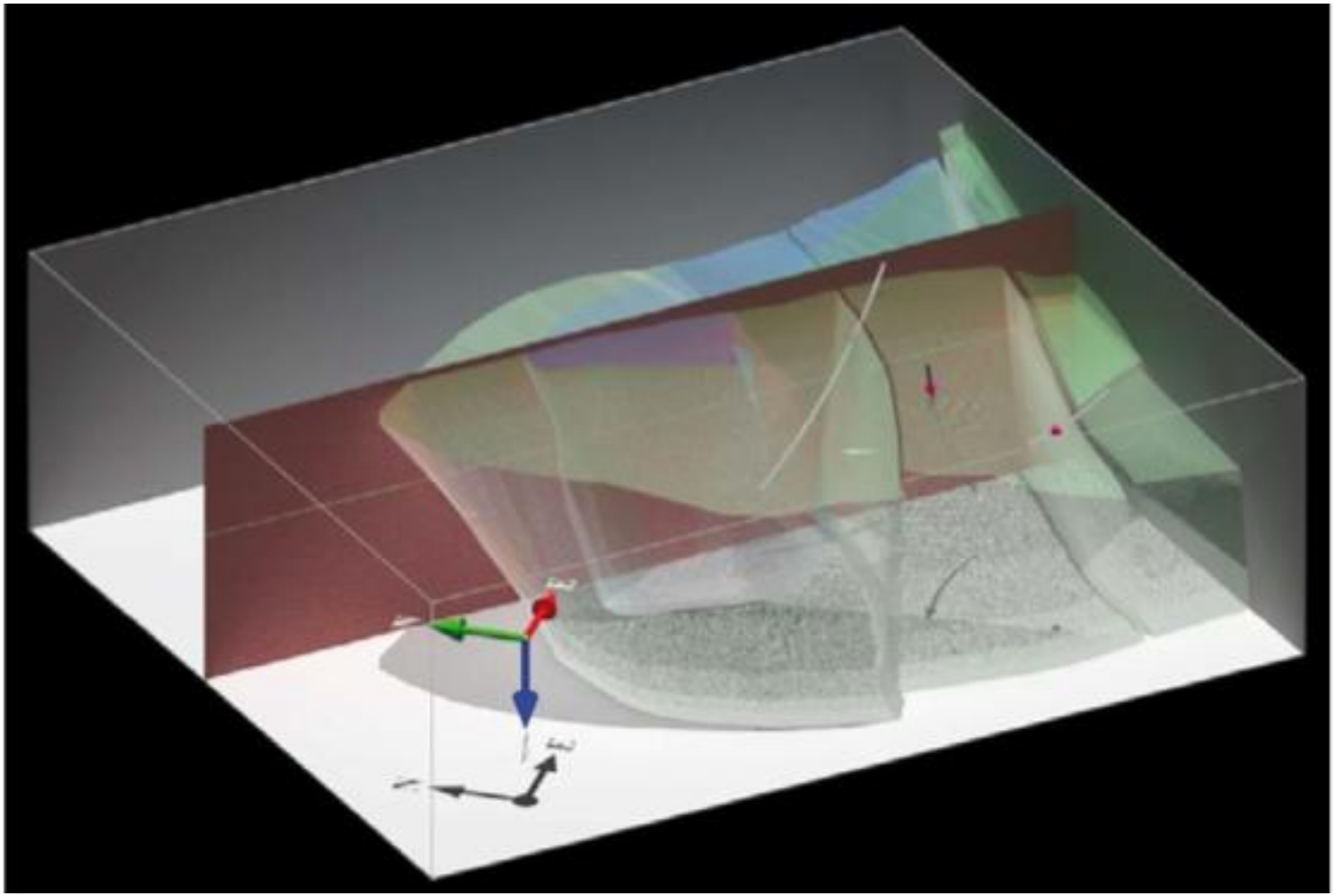


Figure 5-28. *3D-view of the main fracture domains (FFM01 in green and FFM06 in blue) in Forsmark including an inserted cross section plane (in red). The cross section (with dimensions 1,200× 3,800 m and strike 315°) through the domains is shown in 2D in Figure 2-31 to 2-34. Note that deformation zones are omitted from the figure. The repository level (–470 meters) is indicated by a green line projected on the cross section plane. The locations of the five confirmed non-mineralised fractures are illustrated as red spheres. Two of the confirmed non-mineralised fractures occur very close to each other. For this reason only three red spheres are visible in the figure.*

Location of non-mineralized Fractures

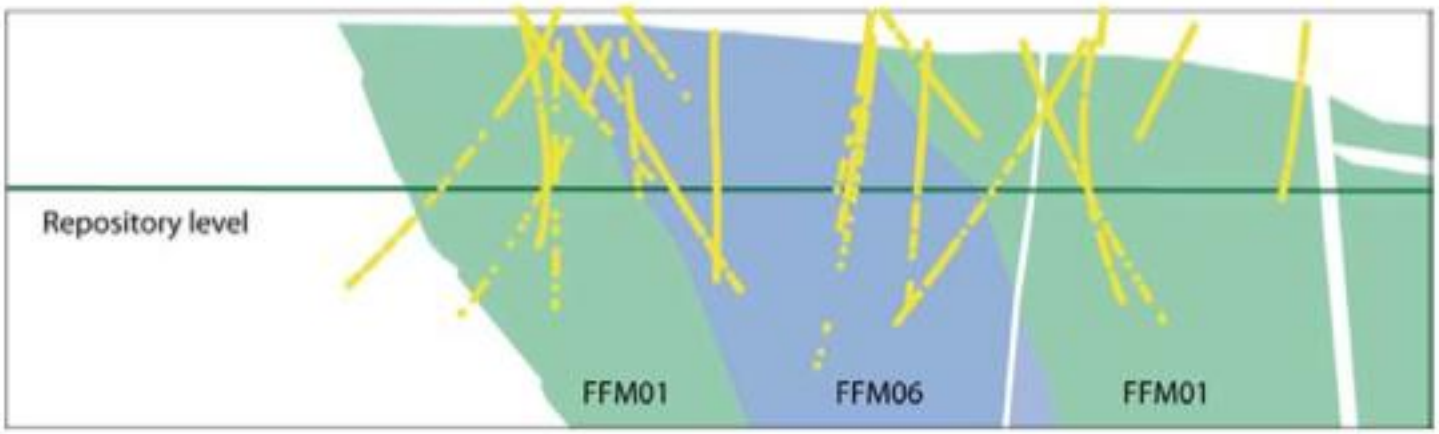


Figure 5-29. *Cross section through the fracture domains in Figure 5-28 showing the borehole intersections of all non-mineralised fractures (yellow dots) at Forsmark.*

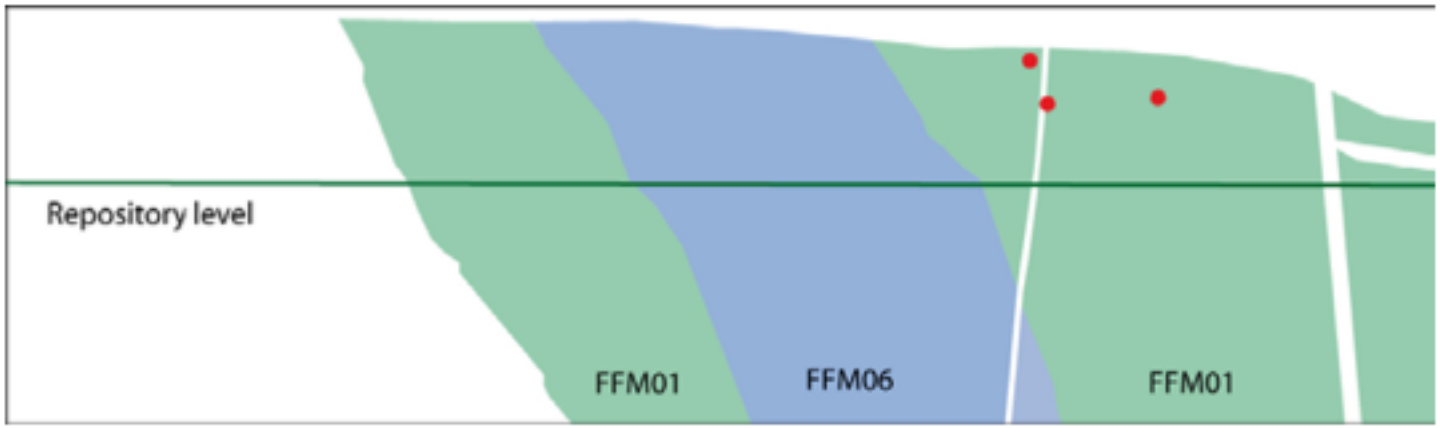


Figure 5-32. *Cross section through the fracture domains in Figure 5-28 showing the borehole intersections of the five confirmed non-mineralised fractures (red dots) at Forsmark. Note, two of the confirmed non-mineralised fractures occur very close to each other, which is why it appears as if only three non-mineralised fractures were confirmed.*

Findings from R-11-02

- We found five of fractures subjected to detailed investigations were non-mineralised; all these fractures were identified in cores from Forsmark. Groundwater flow was detected in three of these fractures; all of them are sub-horizontal to gently dipping and occur at a depth > –250 m.a.s.l.
- It was not possible to draw any conclusions in terms of age of these fractures, because there were no fracture minerals to analyse. We cannot exclude that these fractures were opened up and became water conductive during the Quaternary glaciations or during the post-glacial Holocene period. However, based on the knowledge of fracture generations in Forsmark from previous studies, we suggest that fluid flow in these fractures is not older than Late Palaeozoic.

Forsmark Site Visit

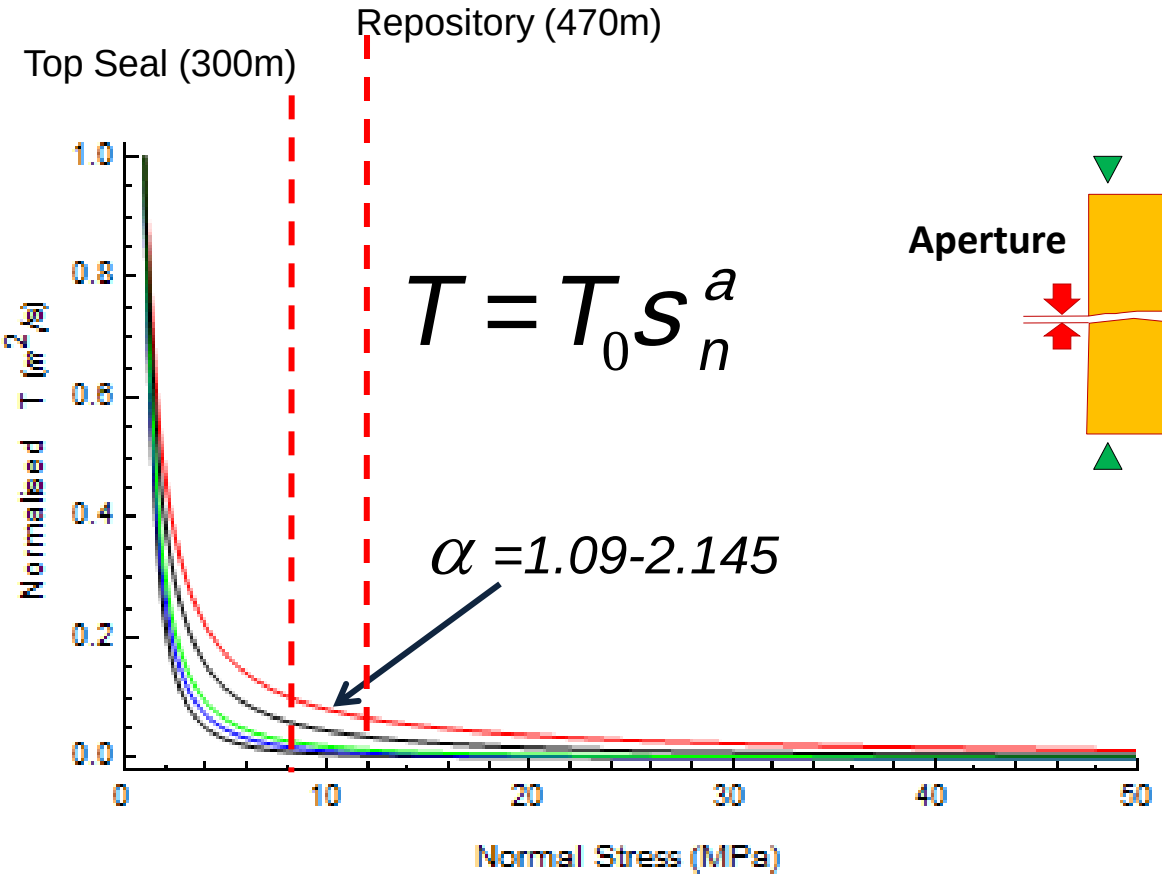
Topics for discussion:

1. Future changes in hydraulic fracture properties
2. Data supporting transmissivity of reactivated fractures

Laboratory versus in-situ (What data/relationships to use for large scale modelling?)

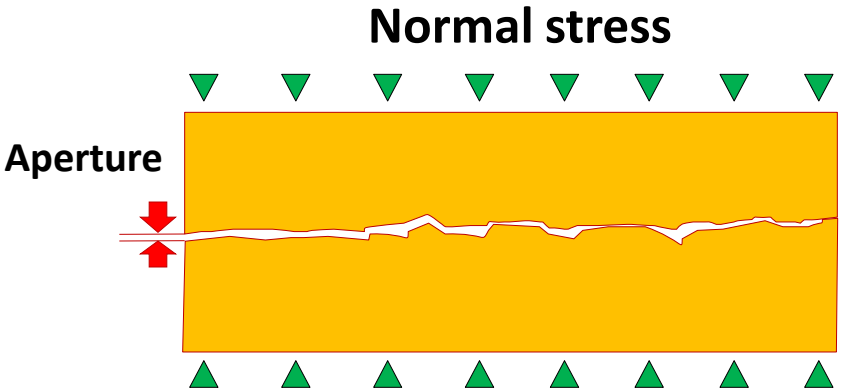
- Sample Disturbance: Laboratory samples
- Different scales:
  Lab(mm) versus in-situ (1 to 100's metres)
- Range of loading is large in Laboratory tests
- Each load-unload tests produces different results:
  Which results should be used to describe in-situ
- Boundary conditions:
  in-situ can be poorly constrained compared to Lab
- Different loading/unloading path
- Most fractures formed >100s millions of years ago

Transmissivity vs stress: Laboratory scale



$$T = T_0 s_n^a$$

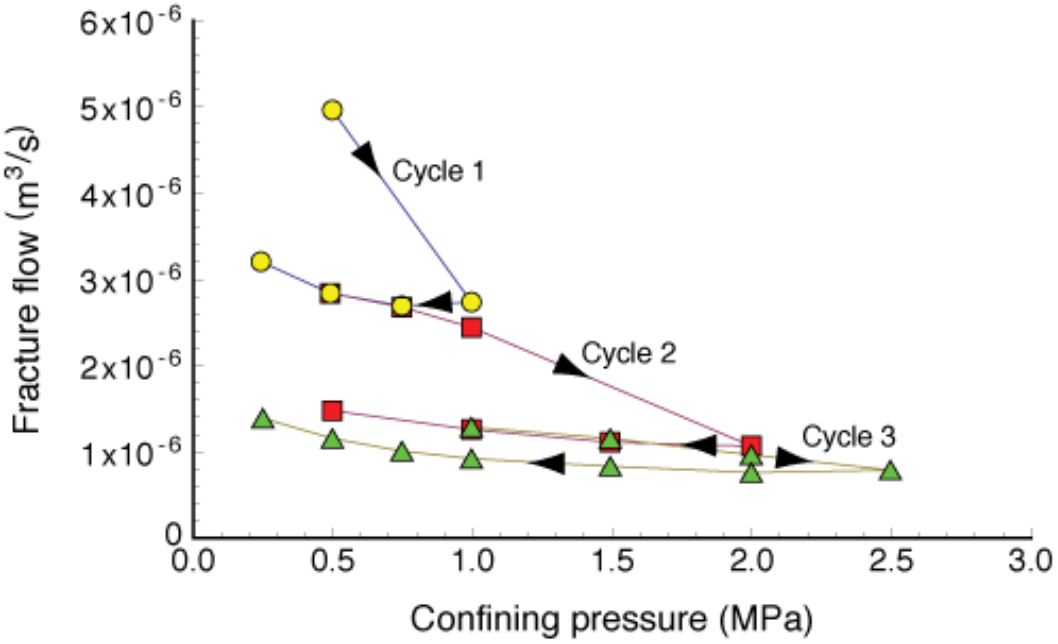
α =1.09-2.145



Olsson, 1998
Iwano & Einstein 1995
Raven & Gale 1985

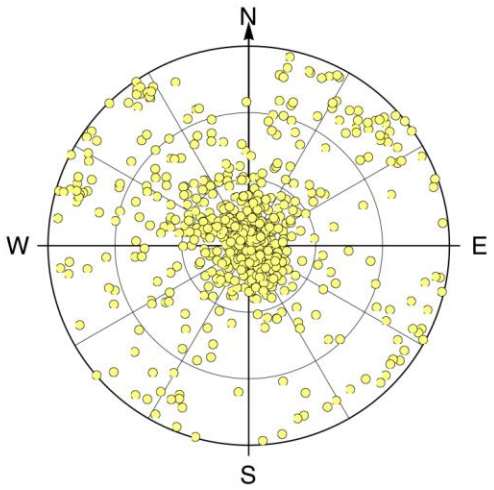
Indraratna and Ranjith (1999) conducted a series of laboratory flow tests on natural fractures in granite. They concluded that the flow rate decreases significantly during the increase in confining stress for the first loading cycle. When the confining stress exceeds 10 MPa, little or no decrease in flow occurs, irrespective of the type of permeating fluid, air or water.

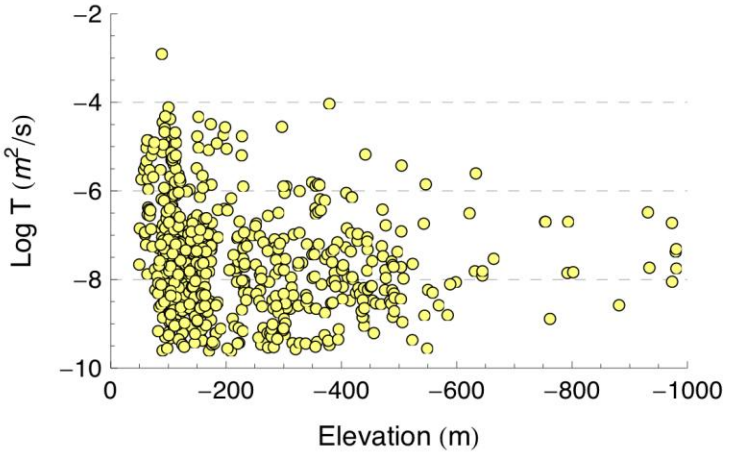
Flow-stress: Laboratory scale

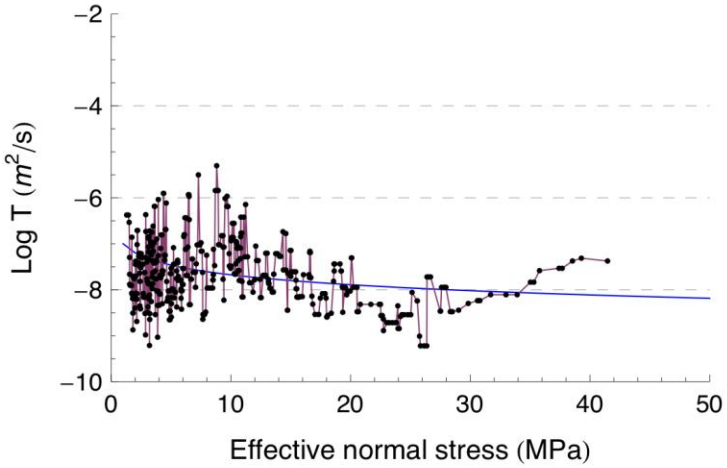


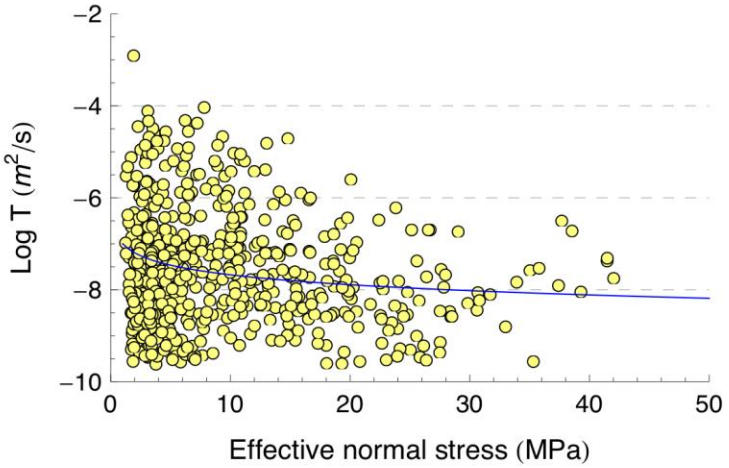
The findings from the laboratory tests clearly show a coupling between flow and normal stress but the strength of the coupling appears to be related to the fracture geometry, stress history and stress magnitude. When the normal stress exceeds 10 MPa coupling is very weak and the coupling is also much less pronounced from repeated loading cycles even at very low confining stresses.

Forsmark 613 PFL measurements



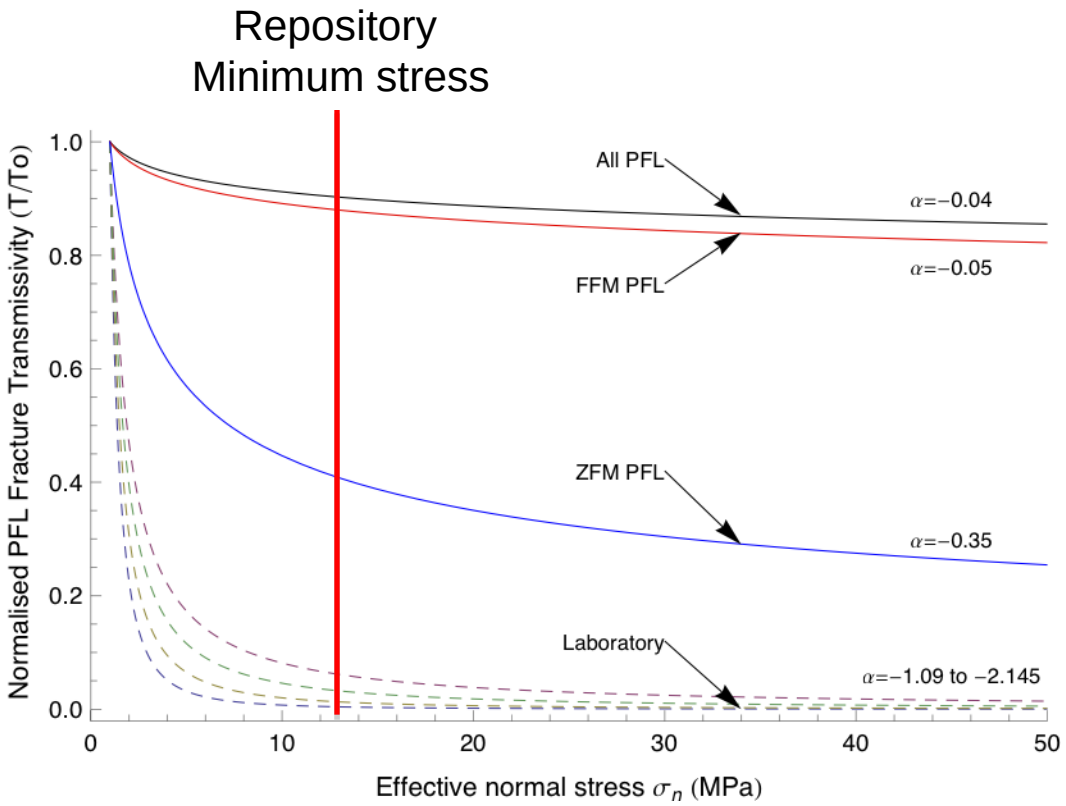






Martin & Follin R-08-69 Review of possible correlations between *in situ* stress and PFL fracture transmissivity data at Forsmark

Summary



$$T = T_0 s_n^a$$

- There is not sufficient evidence to support the notion that the magnitude of the flow along the fractures at Forsmark is controlled by the current in situ stress acting on the fracture. The majority of the fractures formed more than 1 billion years ago and the current stress state has only been active for the past 12 million years. It is more likely that the transmissivity values are controlled by fracture roughness, open channels within the fracture and fracture infilling material.

Findings

In the present work, systematic analyses are carried out to explore possible relationships between the PFL fracture transmissivity data and the normal stress acting on each PFL fracture. The main findings from these analyses are:

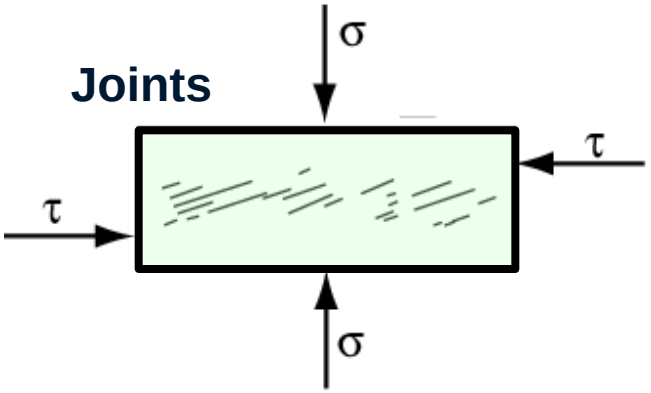
1. No relationship is found between PFL fracture transmissivity and normal stress for the steeply dipping fractures. The normal stress ranged from 10 to 40 MPa. /Indraratna et al.1999/ note that when the confining stress on laboratory samples exceeds 10 MPa, little or no decrease in transmissivity occurs.
2. There is some evidence that the PFL fracture transmissivity of the gently dipping fractures decreases with depth. However, because both the frequency of gently dipping open fractures decreases with depth and the normal stress is also increasing with depth it is not possible to sort out cause and effect for these gently dipping PFL fractures. The gently dipping ZFM_PFL show the strongest correlation between stress and transmissivity. For these zones the effective normal stress is in the range of 1 to 13 MPa.

Data supporting transmissivity of reactivated fractures

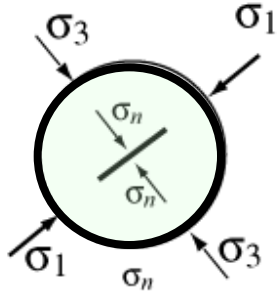
Do any of our existing fractures show reactivation potential?

- Flow enhanced on **joints** when the normal stress acting on the fracture is at a minimum
  D-> 0 to 1.
  Ferrill et al., (1999) based on groundwater flow studies at Yucca Mountain, suggested a value of *D*=0.8 as an indicator for potentially dilatant fractures

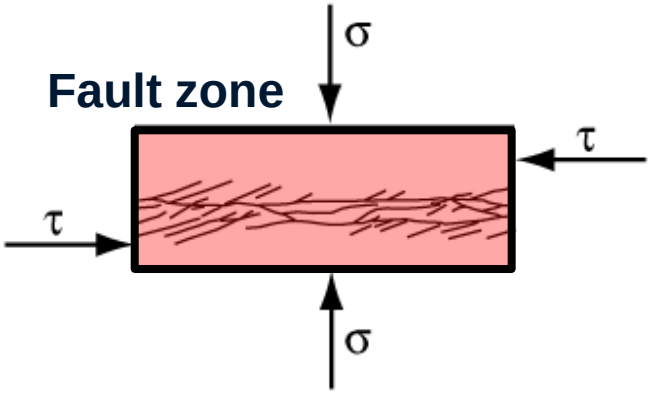
- Flow enhanced along **faults** when fractures are critically stressed S>0.6.



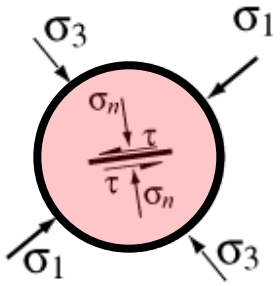
Dilation Potential



$$D = \frac{\sigma_1 - \sigma_n}{\sigma_1 - \sigma_3}$$

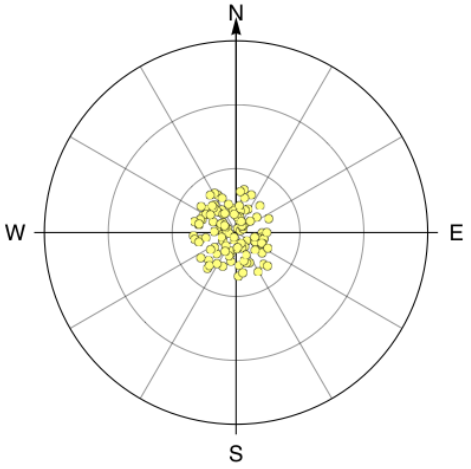


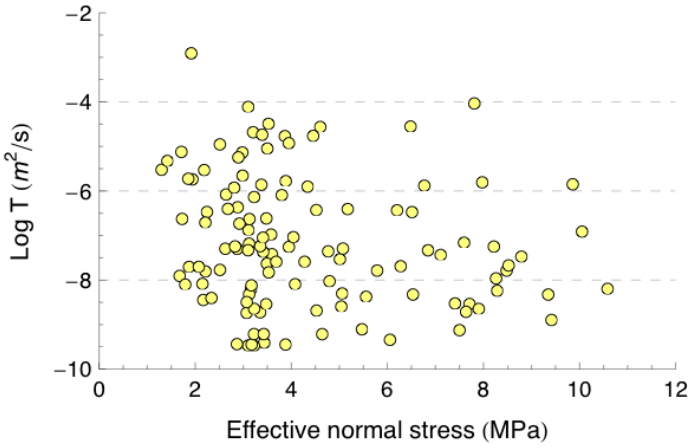
Slip Potential

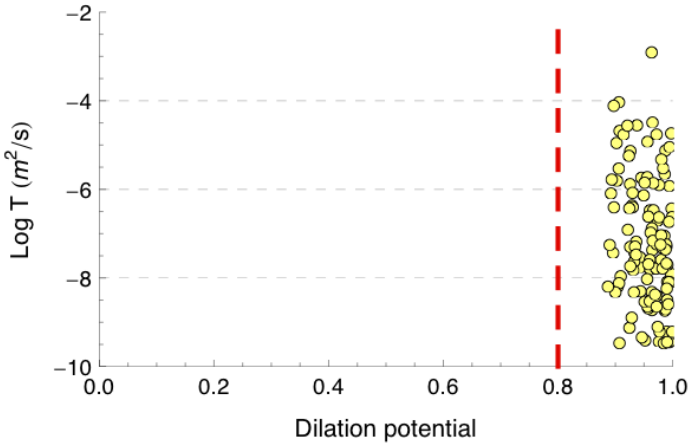


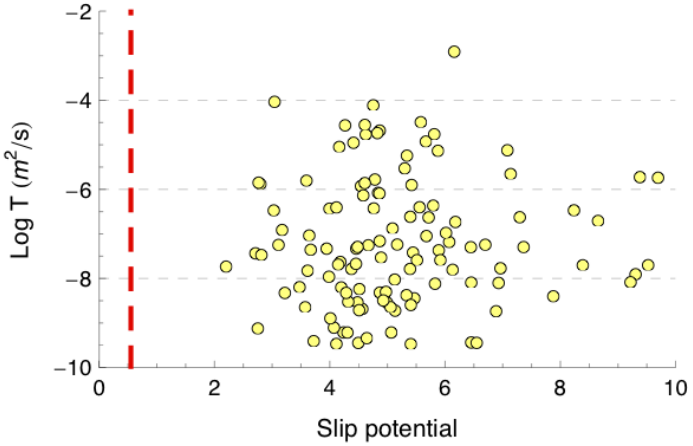
$$S = \frac{\tau}{\sigma_n}$$

Gently dipping fractures (potentially re-activated fractures)









Summary of reactivation (slip and dilation) potential and Transmissivity

Table 5-1. Comparison of the transmissivity values and the dilation (D) and slip (S) potential for PFL fractures in deterministically modelled deformation zones.

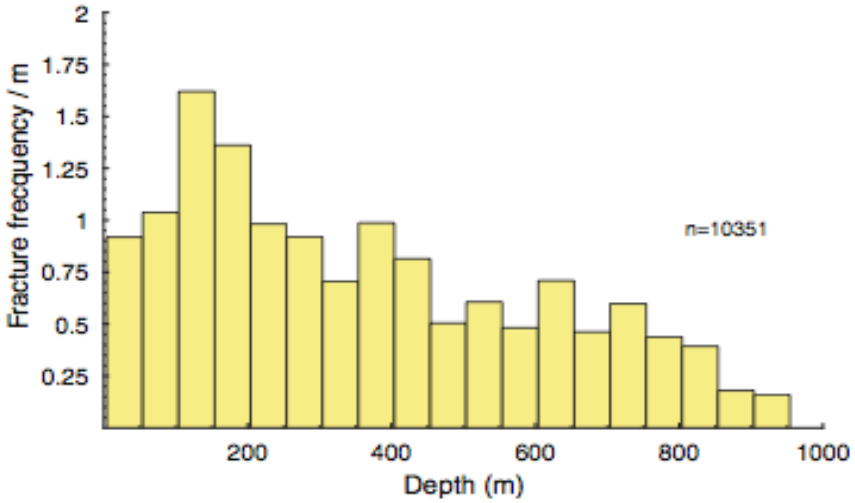
	Number PFL	*D* Mean	*S* mean	Log[T] (m^2/s)		
				Min	Mean	Max
Gently dipping	120	0.95	3.6	-9.47	-7.16	-2.9
NE-SW steeply dipping	42	0.07	0.37	-9.56	-7.88	-4.7
NW-SE steeply dipping	47	0.08	0.39	-9.35	-7.17	-4.7

Summary

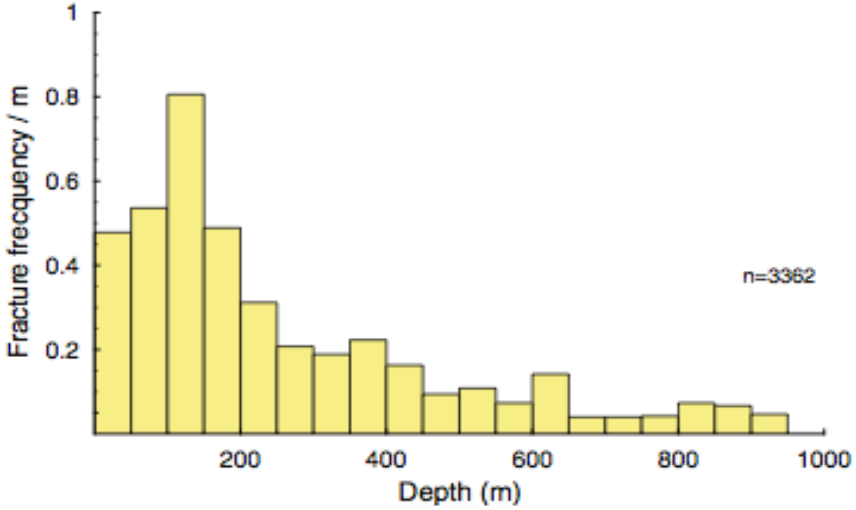
- **Future changes in hydraulic fracture properties**
  1. We have no evidence that new fractures will develop at repository depth.
  2. We examined stress-flow coupling for laboratory and in-situ fractures
  3. Data suggests the lab relationship likely overestimates the coupling
  4. Our analyses examined the effect of both the laboratory and in-situ coupling on repository performance – No significant difference.
- **Data supporting transmissivity of reactivated fractures**
  1. We examined the transmissivity values of existing fractures and deformation zones.
  2. The gently dipping fractures showed they are likely in a reactivation state, consistent with the SDM Model.
  3. We find no significant difference in the transmissivity values for the non reactivated fractures and the reactivated fractures at the depth of the repository.

Fracture & Deformation Zone Properties

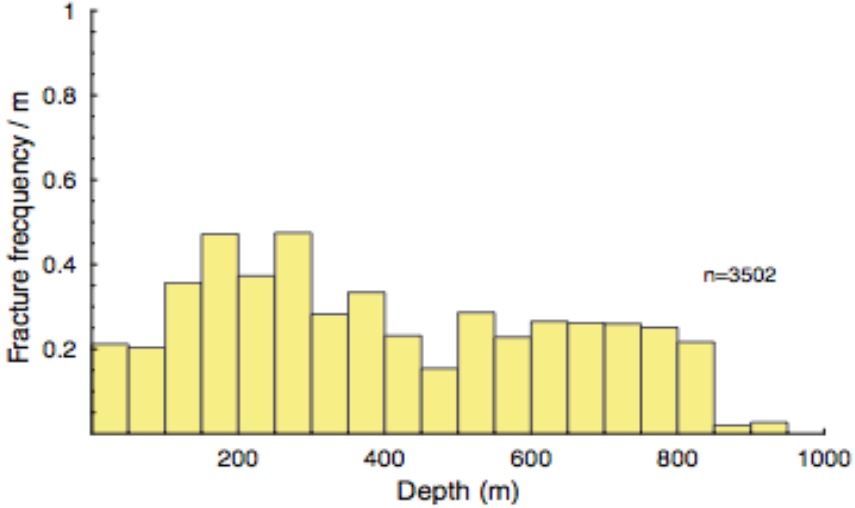
Steeply Dipping Deformation Zone



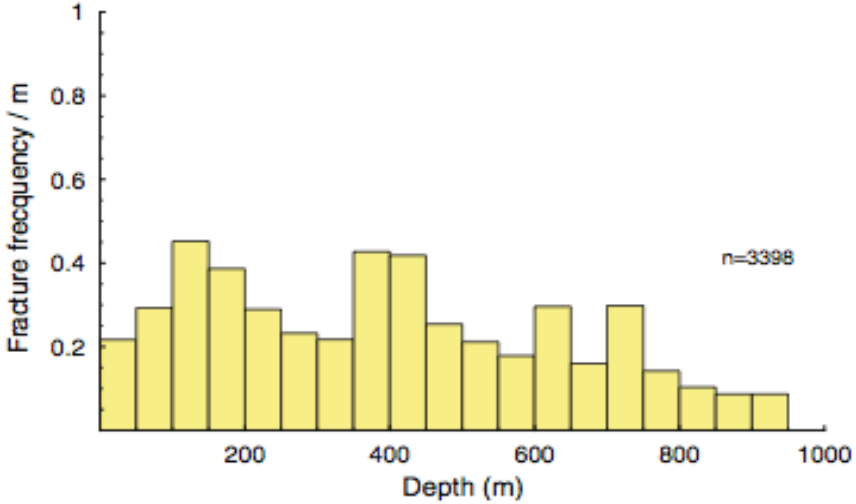
(a) All open fractures



(b) All gently dipping ($< 20°$) open fractures.



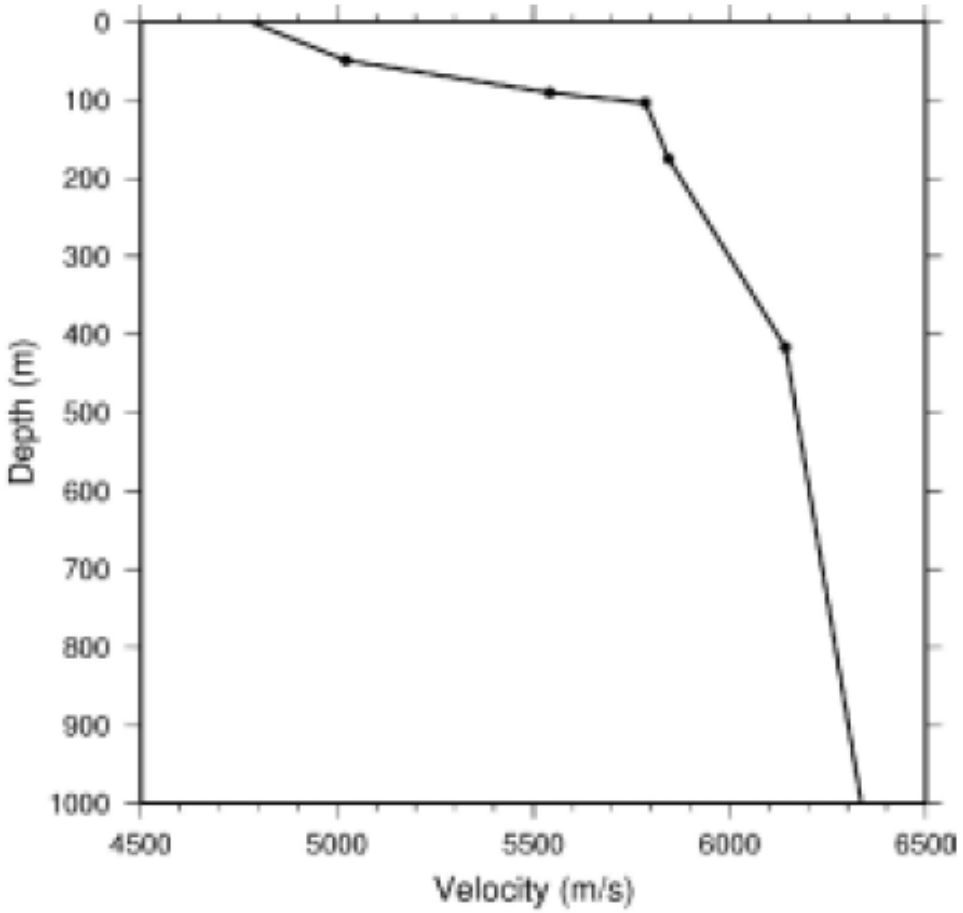
(c) All steeply dipping ($> 70°$) open fractures.



(d) All open fractures dipping $> 20°$ and $< 70°$.

Figure 2–8: *All open fractures from Forsmark boreholes that are visible on the BIPS log. Data obtained from SICADA 2007 April 23.*

Rock Mass P-Wave velocity



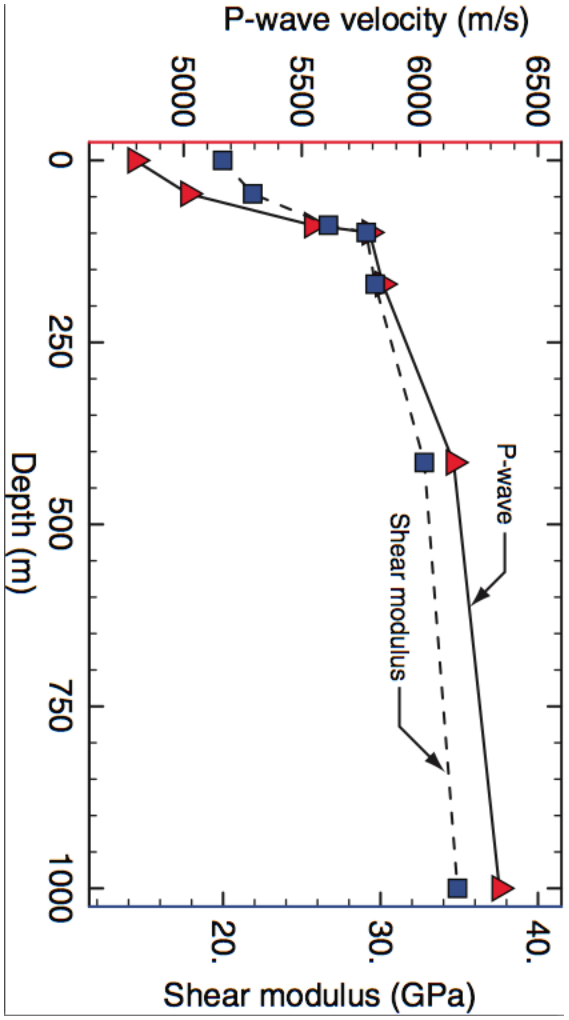
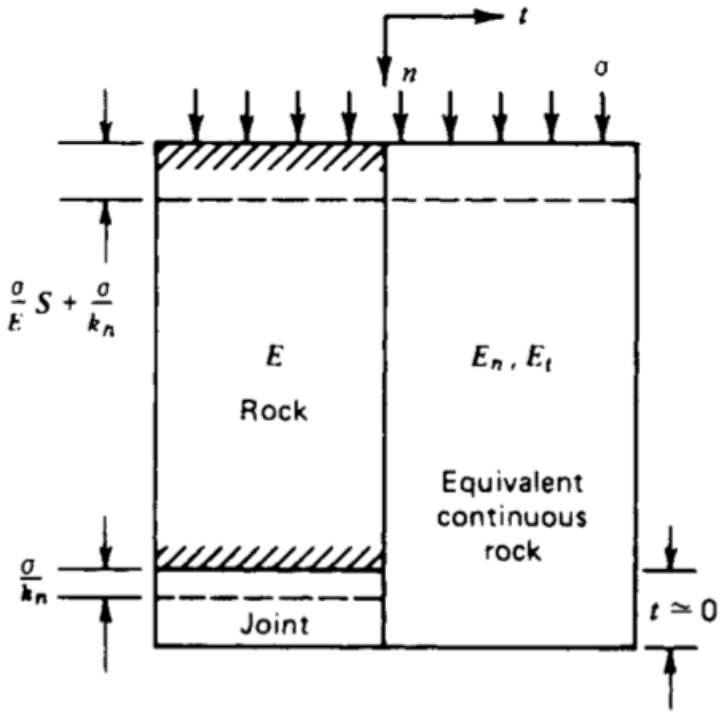


Figure 4-19. Initial 1D P-wave velocity model for the Forsmark area based on first arrival times from the Orion stations. (SKB **R-02-43**)

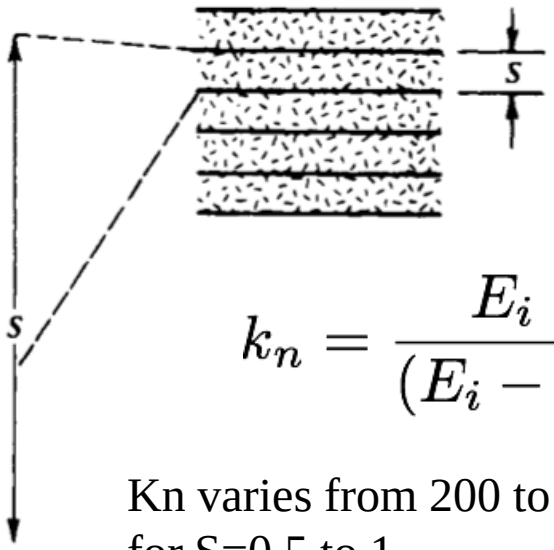
Reports by Carlsson & Olsson

Large Scale in-situ tests on stress and water flow relationships in fractured rock (1986)

- Plate load tests (1 m Diameter)
  - At 2 MPa E_{rm}=40 GPa
  - E_i intact rock = 50 GPa



$$\frac{1}{E_{rm}} = \frac{1}{E_i} + \frac{1}{k_n \times s}$$



$$k_n = \frac{E_i \times E_{rm}}{(E_i - E_{rm}) \times s}$$

Kn varies from 200 to 400 MPa/mm
for S=0.5 to 1

Singö Deformation Zone

Glamheden et al. 2007. Mechanical modelling of the Singö deformation zone. Site descriptive modelling Forsmark stage 2.1. Svensk Kärnbränslehantering AB. Report R-07-06.

Convergence results were used to back calculate the large scale stiffness of the Singö Deformation Zone

Table 12-1. Typical rock mechanical parameters of the Singö deformation zone for normal stresses in the range of 5–20 MPa.

Normal stiffness (MPa/m)	Shear stiffness (MPa/m)	Cohesion (MPa)	Friction angle (degrees)
200	10–15	0.4	31.5

Fracture properties from SDM Site: TR-08-05

Table 7-4. Results from direct shear tests on open fractures in fracture domain FFM01 and deformation zones intersecting the target volume. The tests include 29 samples from FFM01 and 10 samples from three DZ.

Parameter	FFM01		DZ	
	Mean/stdev Uncertainty	Min-Max	Mean/stdev Uncertainty	Min-Max
Normal stiffness (MPa/mm)	656/396 ±22%	159–1,833	662/729 ±68%	167–2,445
Shear stiffness, K_{s20}, (MPa/mm)	34/10 ±11%	18–52	31/8 ±16%	19–44
Peak friction angle (°)	37/3 ±3%	29–42	35/2 ±4%	32–38
Peak cohesion (MPa)	0.8/0.3 ±14%	0.2–1.3	0.8/0.5 ±39%	0.0–1.7
Residual friction angle (°)	34.9/3.4 ±4%	28–42	35/2 ±4%	30–37
Residual cohesion (MPa)	0.3/0.2 ±24%	0.1–0.8	0.3/0.2 ±41%	0.0–0.6

Note: Shear stiffness at 20 MPa normal stress. The uncertainty of the mean is quantified for a 95% confidence interval. Minimum and maximum truncation values are based on the observed min' and max' for the tested population.