Quantification of coupled hydro-mechanical processes in deep hydraulically transmissive fractures by downhole field tests and modelling

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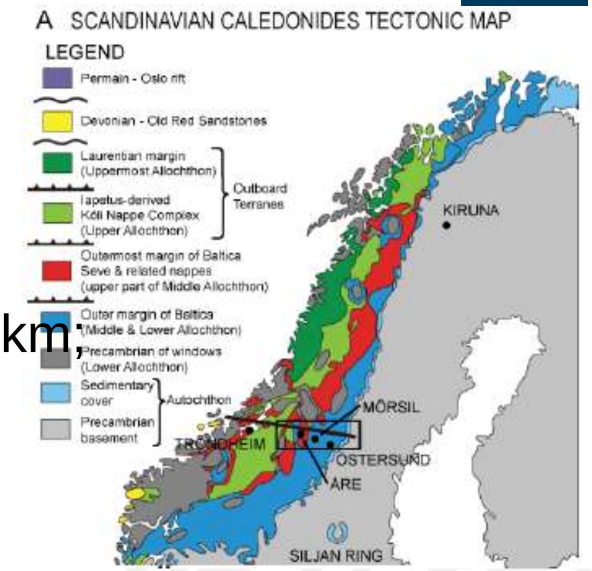
Outline of the SGU project (2019-2021)

- Coupled hydro-mechanical (HM) processes are of key importance for many important geological applications
- We bring together two major infrastructures to address this
  - ICDP drilled 2,5 km deep investigation borehole COSC-1 in Åre
  - New SIMFIP HM measuring method developed at LBNL, USA
- Coupled HM measurements were conducted at selected transmissive and non-transmissive fractures in COSC-1 borehole, along with micro seismic and aseismic responses in June 2019
- The results are being analyzed and modelled to obtain an improved understanding of the coupled HM processes in deep hydraulically transmissive fractures.
- Collaboration between Uppsala University, financed by SGU, and Lawrence Berkeley National Laboratory (LBNL), financed by US-DOE

COSC-1 deep borehole in Åre Sweden



- To study Collisional Orogeny in the Scandinavian Caledonides (COSC). Part of ICDP. Two coreholes up to 2.5 km;

- COSC-1, Åre completed;
  - fully cored (99%)
  - suite of geophysical and hydraulic logs and core studies available

Motivation for present study:

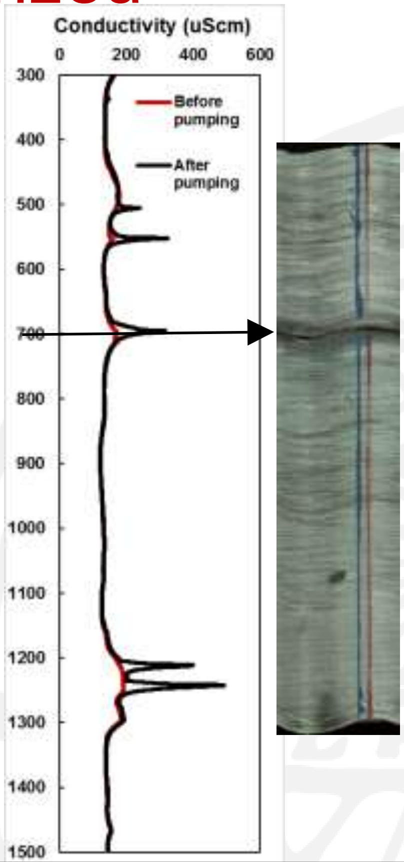
- HM coupling important for many geoscience applications
- Opportunity to have closely coordinated field-modelling study
- Special emphasis in the time-evolution of HM

The flowing fractures in COSC-1 well identified and characterized

- FFEC method was used to identify the conductive zones and to determine the transmissivities, etc (Tsang et al., 2016, Doughty et al., 2017)
- Correlated to geophysical, geochemical data etc. (Dessirier et al., in preparation, 2019)

Peak	Depth (m)	T (m²/s)	h (m)	C (µS/cm)	C (g/L)
1	1243	4E-9 - 5E-9	-42	1700 - 2200	0.9 - 1.2
2	1214	9E-9 – 2E-8	-48	620 - 1150	0.3 - 0.6
3	697	6E-9 - 1E-8	-47	1000 - 1400	0.5 - 0.7
4	553	4E-9 - 7E-9	-50	1800 - 2900	1.0 - 1.6
5	508	2E-9	-50	1800 - 2800	1.0 - 1.5
6	336	1E-10 - 2E-10**	0	1200 - 2900	0.6 - 1.6
7	288	7E-9 – 8E-9***	3 – 7	380	0.2

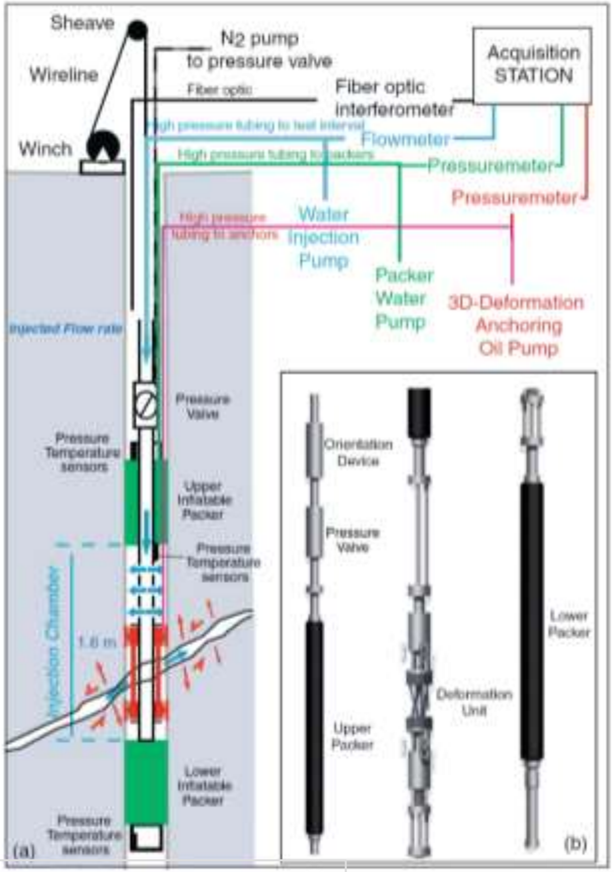
- Good basis for coupled HM studies using an advanced downhole tool



Tsang et al, 2016, Hydrogeol Jour 24(6) Pp 1333-1341
Doughty et al 2017, Hydrogeol Jour 25(2) Pp 501-517

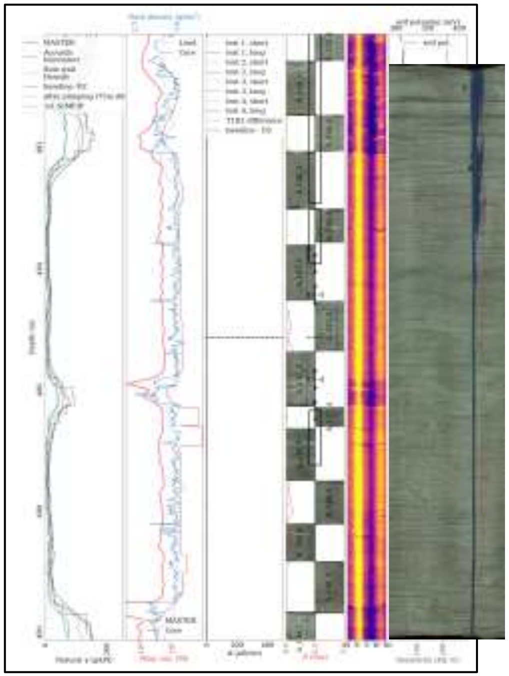
SIMFIP tool to measure coupled HM behavior in the borehole

- SIMFIP= Step-rate Injection Method for Fracture in-situ Properties
- Unique method and tool developed by LBNL (Guglielmi et al., 2014) to study the detailed time-evolution of coupled HM effects
- Provides real-time simultaneous measurements of pressure, flow, and rock deformation in packered zones
- Previous tests made in sites in South Dakota, Japan and Switzerland

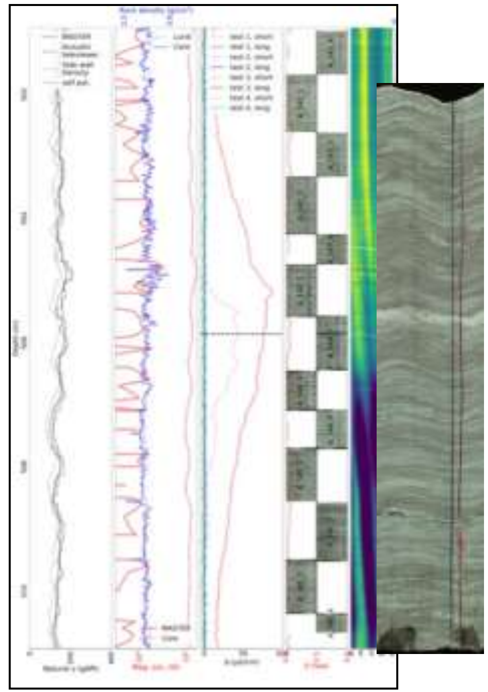


Guglielmi et al., 2014. Rock Mech Rock Eng. 47: 303-311

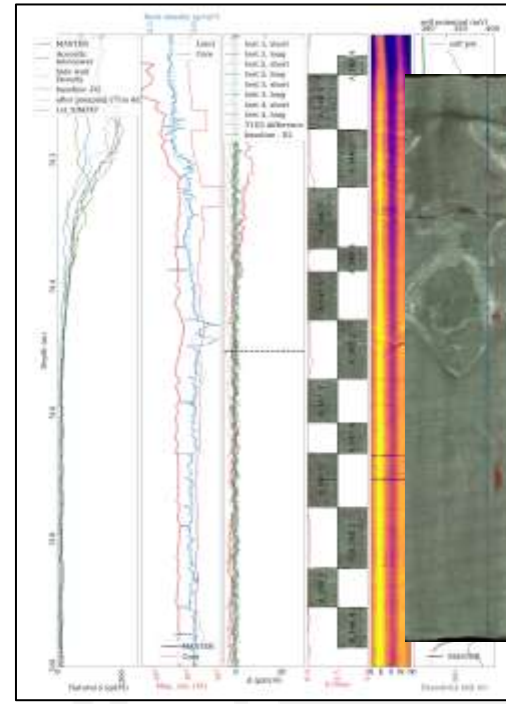
Selection of Test Intervals



Intact No-Flow Zone
485.2 m depth
(including fracturing)



Flowing fracture
504.5 m depth
(opening fracture)



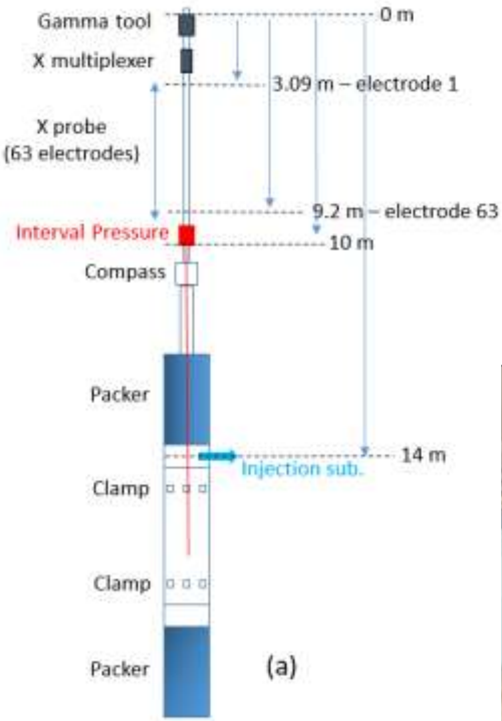
Non-Flowing Fracture
515.1 m depth
(opening fracture)

Positioning procedure

- Positioning important. Accuracy has to be ~ 0.2 m in the 2.5 km borehole
- We found the optimal way is matching γ log profiles to old EC/T/γ data used to locate inflow fractures
- Supporting information: new FFEC test for flowing feature identification

Added 60 electrodes above SIMFIP tool for FFEC logging

Added EC/T/γ probe to the SIMFIP tool



In the field…

Establishing consistency of gamma-profiles

Pump-test for FFEC measurements

Preparing the seismic measurements

In the field…

SIMFIP tool going into the borehole

Carefully lowering all the lines

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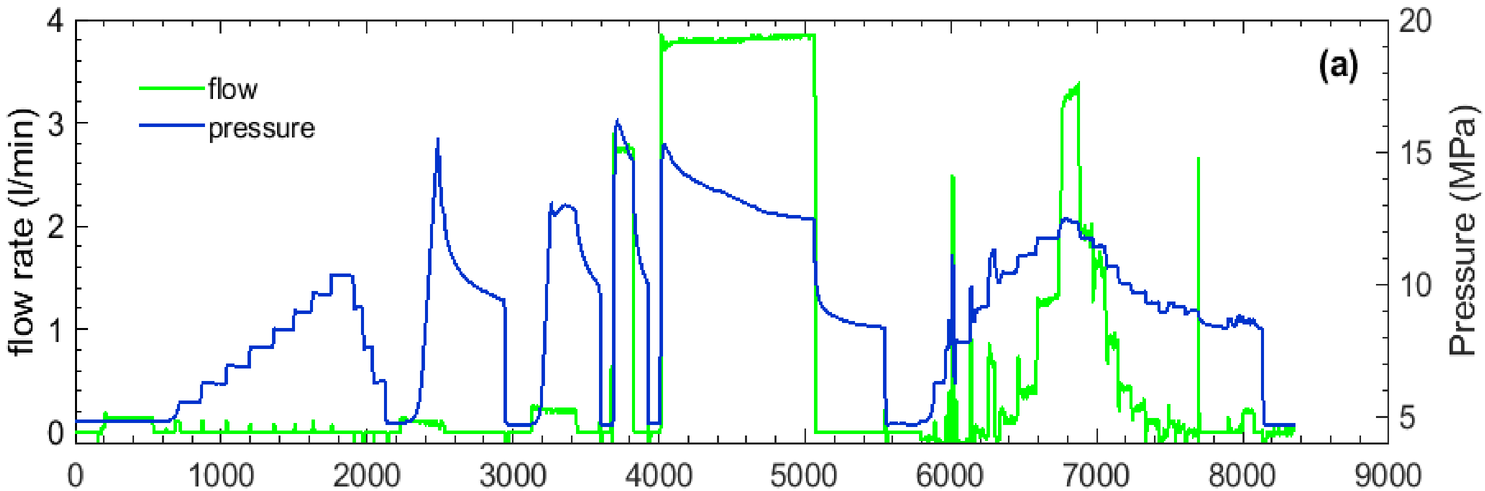
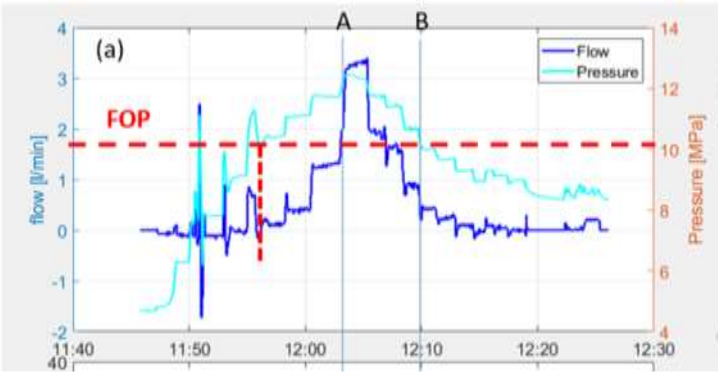
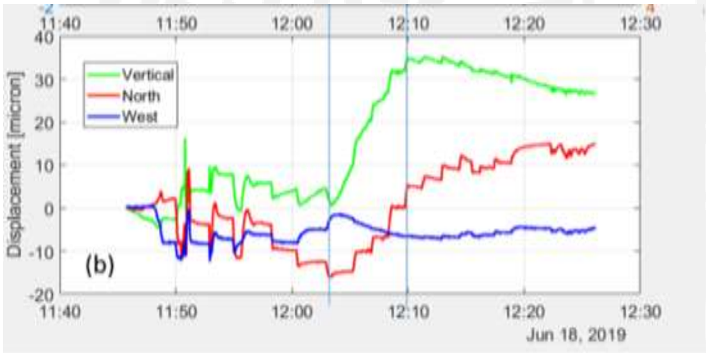
Example of collected data – interval with previously no fracture

Pressure – flow rate data



Deformation data

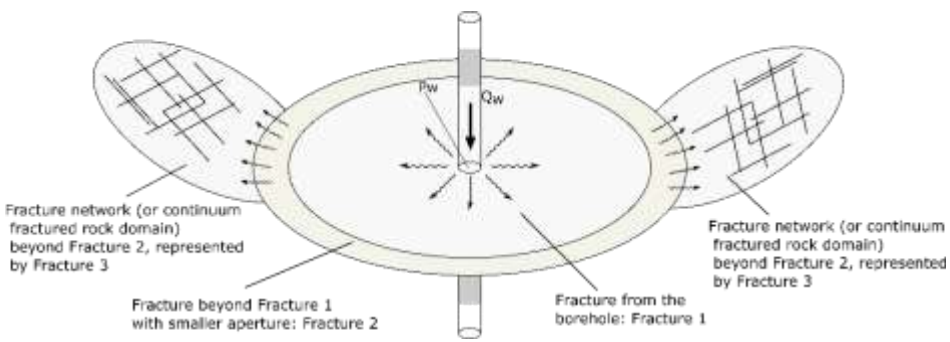


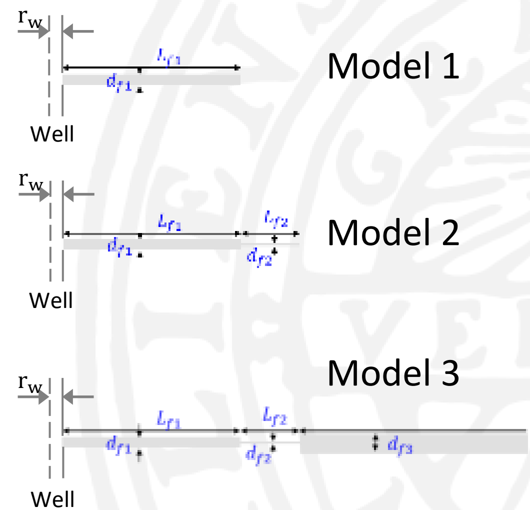


Hydraulic modeling of the SIMFIP packer tests at COSC-1 deep borehole

- We performed a hydraulic model analysis of flow and pressure data at different time intervals of fracturing and fracture opening/propagation.
- The objective is to identify fracturing and fracture geometry at different time stages of the experiment.
- The model can represent the case of several parallel fractures in the borehole section.

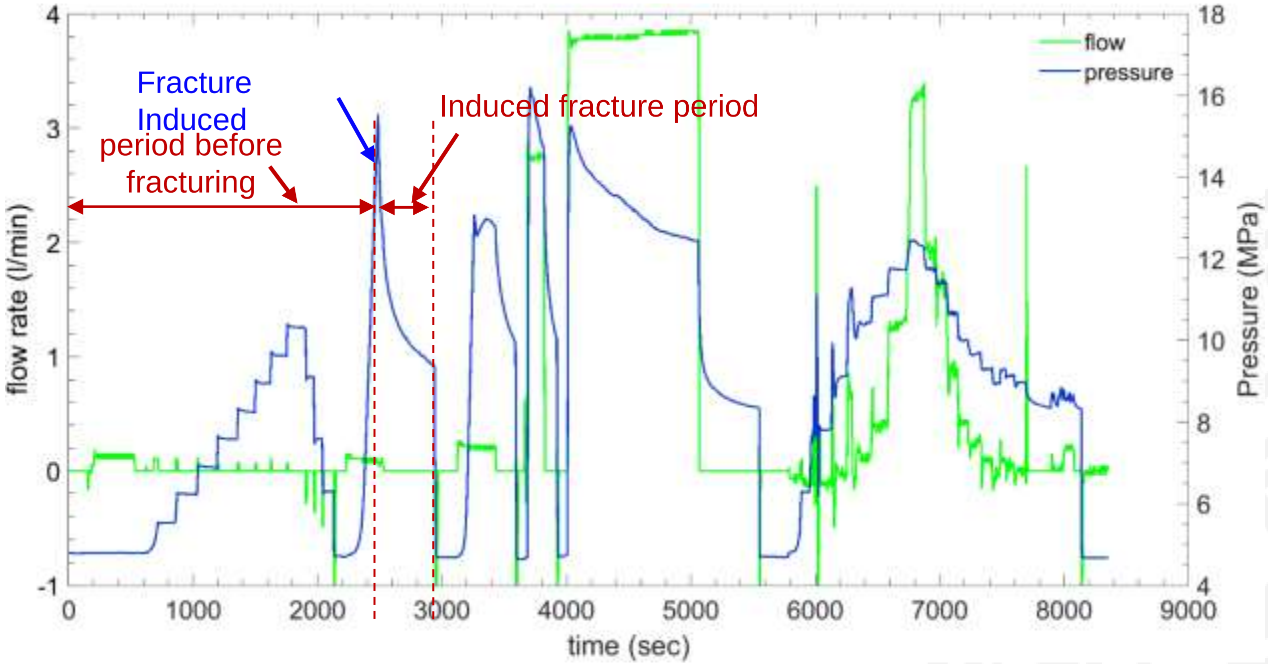
$$d_f = \left(\sum {d_i}^3\right)^{1/3}$$





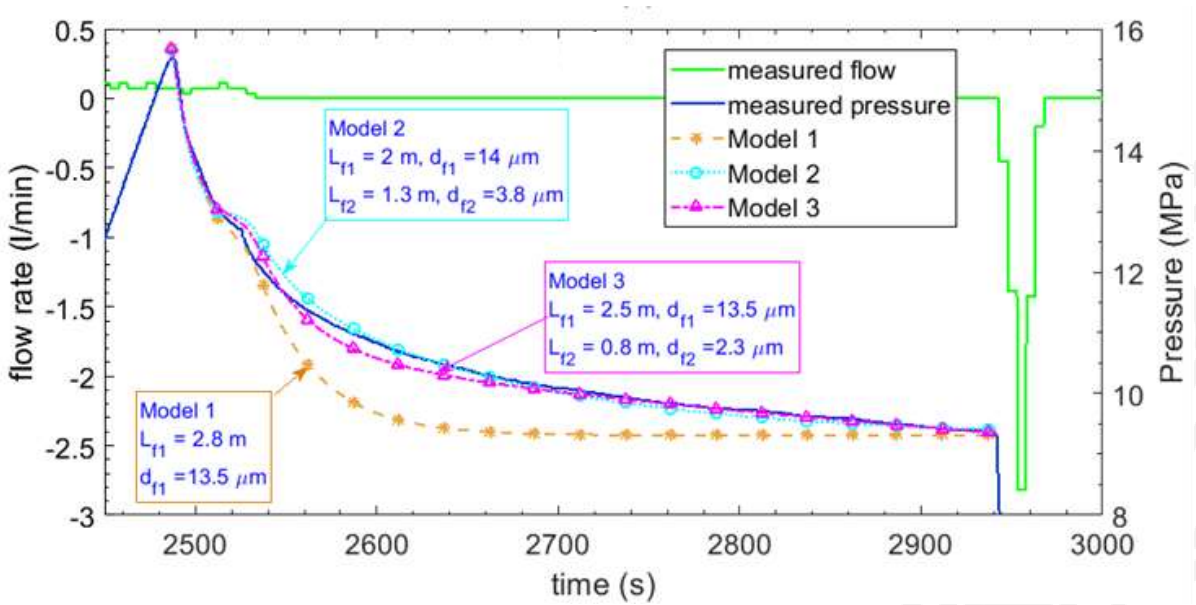
Adopted from Rutqvist et al., 1998. Water Resources Research. 34-10: 2551-2560

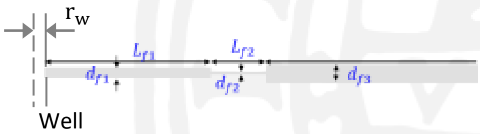
Case 1 – test of section without fracture initially (Intact rock)



- This section initially has no fracture and the flow and pressure data of the period before fracturing are used to find the parameters of the packered borehole interval.
- Then the model is applied to estimate the generated fracture length, aperture, geometry.

Case 1 – Modeling of the induced fracture





- Cracking pressure is 15.5 MPa
- Model 3 is the better conceptual model
- Different parameters control the different parts of pressure evolution

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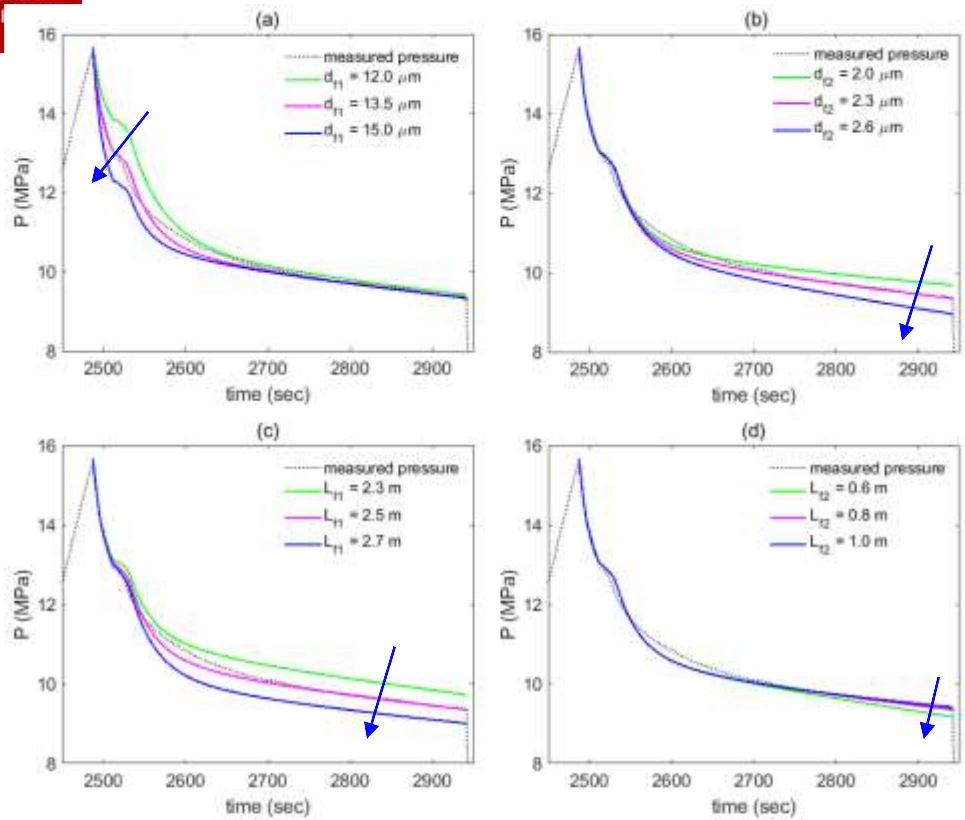
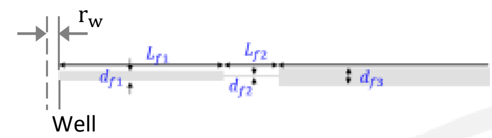
Case 1 – Sensitivity of Model 3 to the fracture parameters





- continuing injection for a period after cracking is important to constrain estimate of aperture of the induced fracture;
- the end-point pressure at the recovery stage after the injection stop provides information on fracture length;
- Aperture of third fracture represents effective permeability of the flow domain beyond the second fracture.

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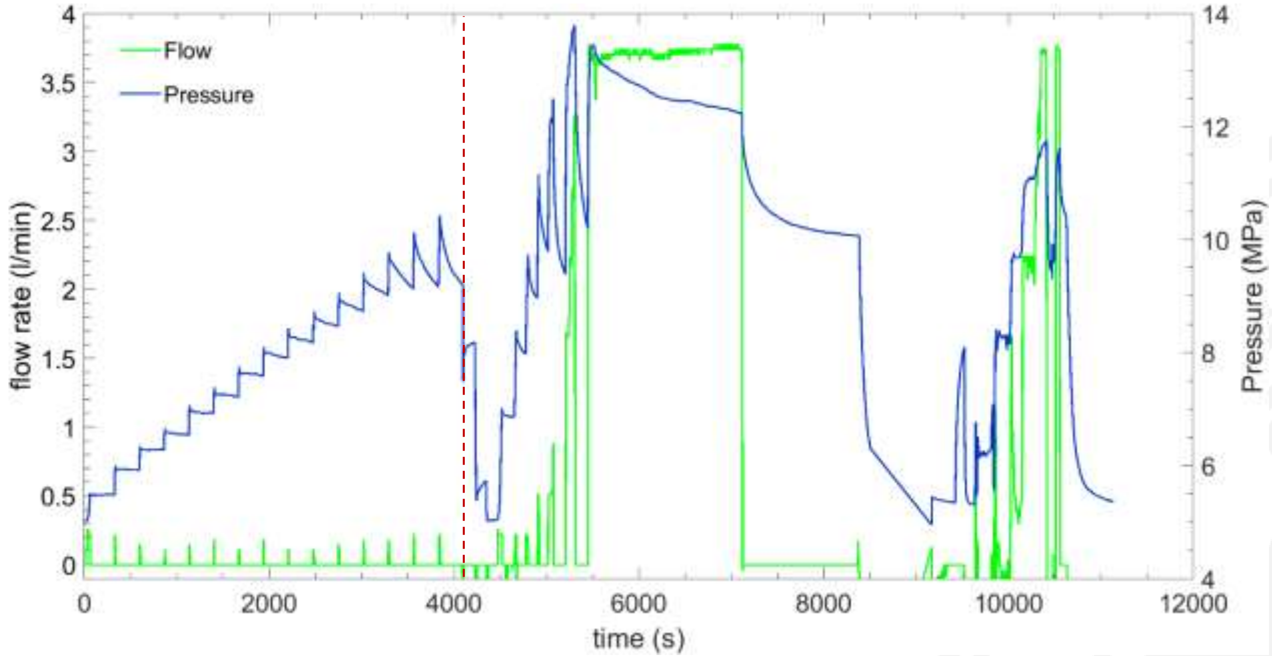
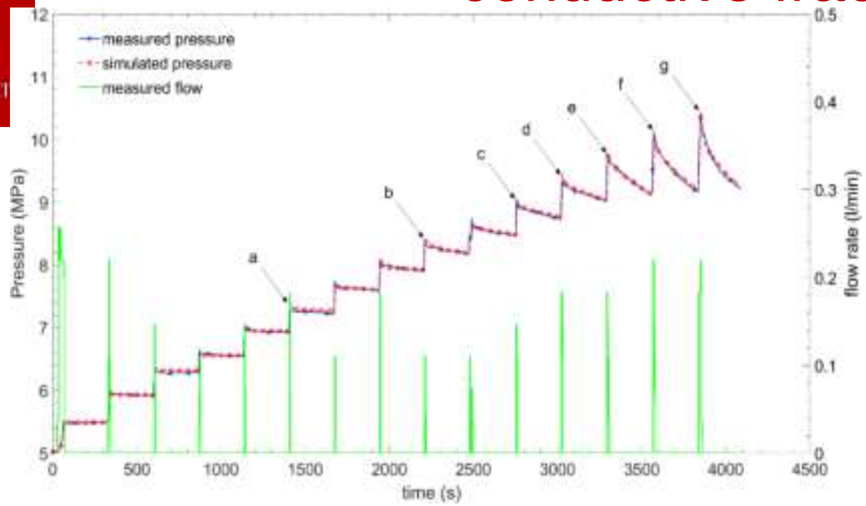
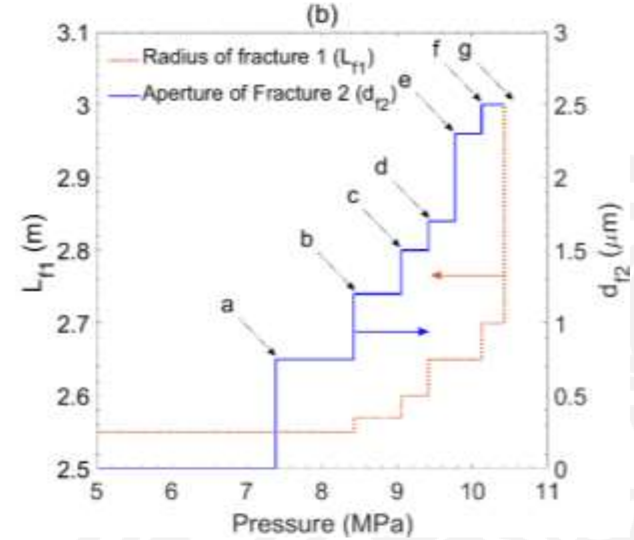
Case 2 – Analysis of the section with non-conductive fracture



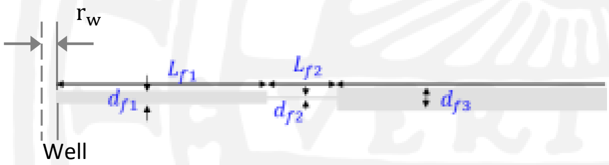
- To model this case, we used the same conceptual model presented for the Case 1 (Section with no initial fracture or intact rock).
- Study so far looks at the first part up to 4650 sec.

Case 2 – Analysis of the section with non-conductive fracture

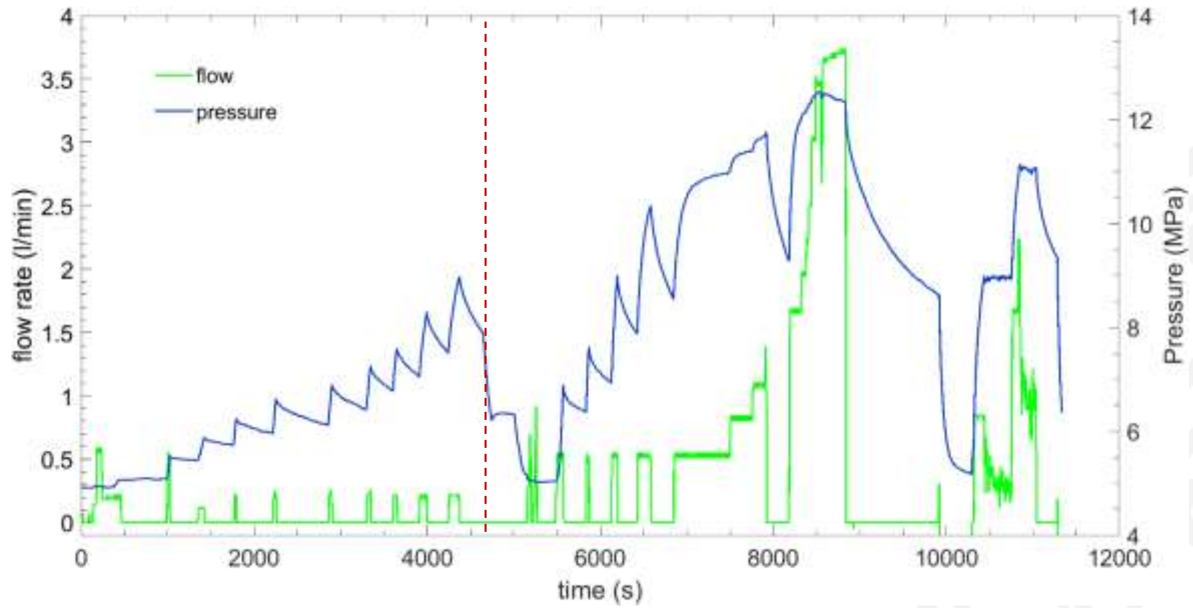




- The modeling result indicates that at pressures above 7.2 MPa the second fracture aperture needs to be changed from zero to 0.5 µm
- Based on the conceptual model, increase in pressure can increase the radius of non-conducting fracture [fracture 1] and aperture of narrow section [fracture 2].

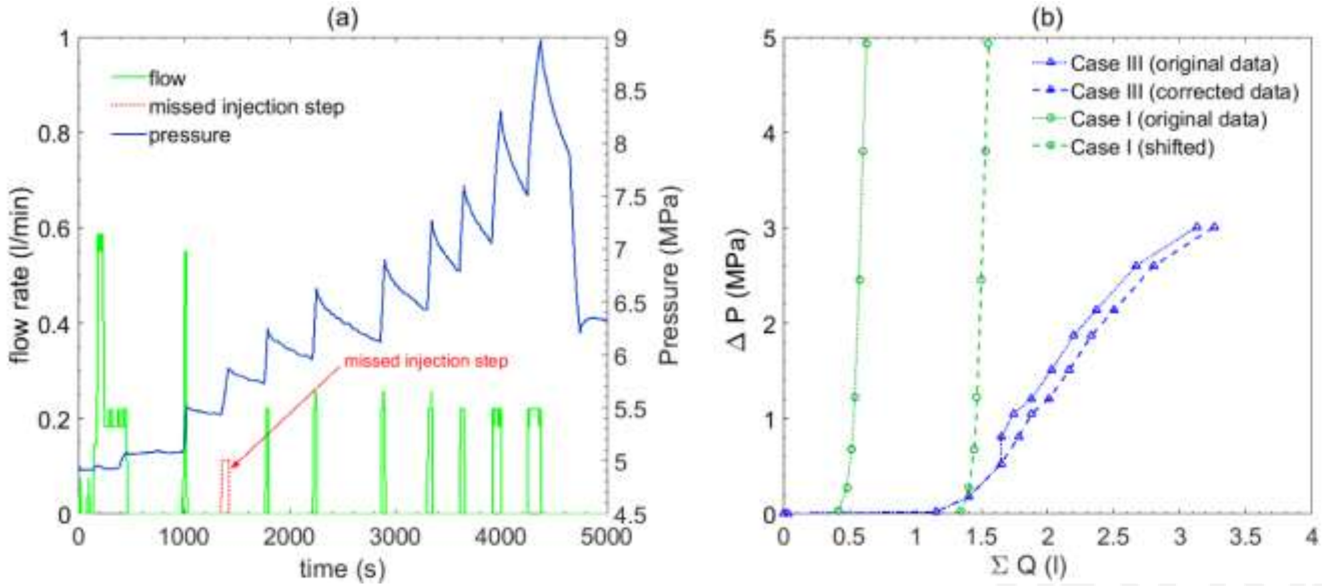


Case 3 – Analysis of the section with conductive fracture



- To model this case, we used the Model 3presented for the Case 1 (Section with no initial fracture or intact rock).
- Study so far looks at the first part up to 4650 sec.

Case 3 – Modeling results for the section with conductive fracture



- A missed injection step is estimated by smoothing the accumulative flow rate vs pressure change [right hand figure].
- The cumulative flow vs pressure change curve shows the section of case 3 is much softer than the borehole section because of presence of conductive fracture.
- The modeling result indicates that a single set of fracture parameter is sufficient to match the measured pressure below 8.3 MPa. Above 8.3 MPa data shows the fracture needs to be opened up.

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Summary and conclusions

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- Unique field experiment has been carried out in COSC-1 borehole in Åre, to determine the coupled hydro-mechanical behavior and rock deformation continuously in time at depths previously not measured with this type of approach
- Three sections: (i) previously non-fractured rock section, (ii) section with non-conductive fracture and (iii) section with conductive fracture were tested
- Seismic activity was continuously monitored
- As first modeling, we present the results from a purely hydrological model allowing to estimate the radius and aperture of the induced and propagated fractures
- The results show that the pressure required for fracturing at the depth of about 500 m (Case 1) is 15.5 MPa, while the pressure required for extension of a initially non-conducting fracture is about 7.2 MPa (Case 2), but the pressure to open up a conducting fracture is estimated to be 8.3 MPa (Case 3).
- Work continues for a more detailed modeling of the full coupled hydro-mechanical behavior as well as comparison to the deformation data

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Thank you

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