Analysis of flow and pressure data for the estimation of fracture generation and propagation - First model results from coupled hydromechanical experiments in COSC-1 borehole in deep crystalline rock, Åre, Sweden

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EGU General Assembly 2020
ERE6.3 FRACTUREs: Breaking the Laws
Friday, 08 May, 16:15-18.00

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Outline

- COSC-1 deep borehole (Åre, Sweden) aimed for scientific investigations.
- Hydromechanical experimenting of fracture generation and propagation using SIMFIP tool.
- The analysis of flow and pressure data using hydraulic modeling to estimate the fracture parameters at different stages of experiment.

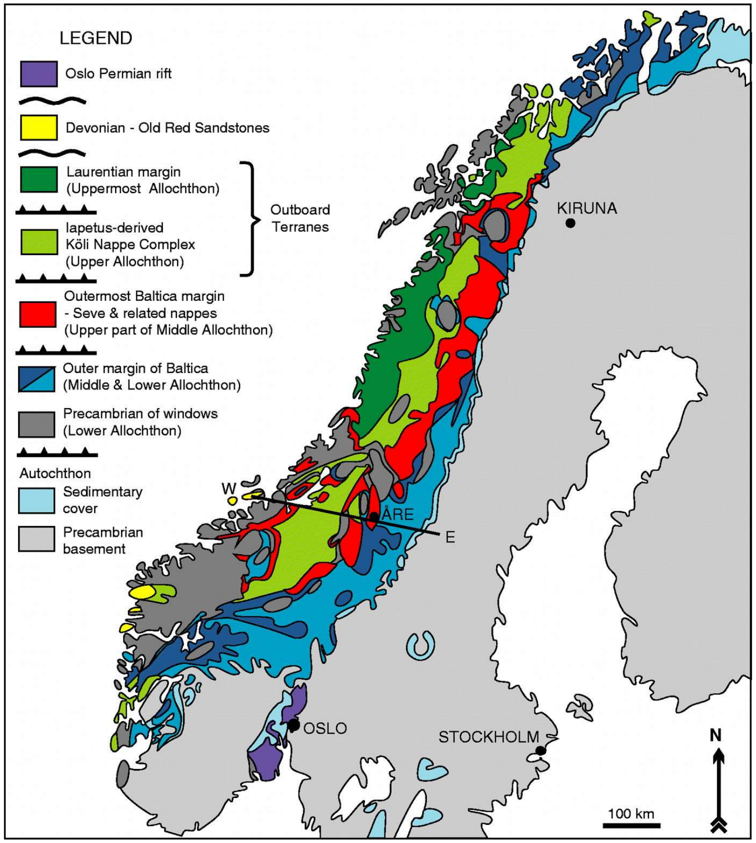
COSC-1 deep borehole in Åre Sweden

To study Collisional Orogeny in the Scandinavian Caledonides (COSC). Part of ICDP.

COSC-1 borehole intersects 2.5 km of crystalline rocks.

Extensive characterization of core and borehole – many fractures determined from ATV.

Transmissive fracture zones in borehole from 200-2000 m were identified and characterized using FFEC logging analysis (Tsang et al, 2016, Doughty et al, 2017)

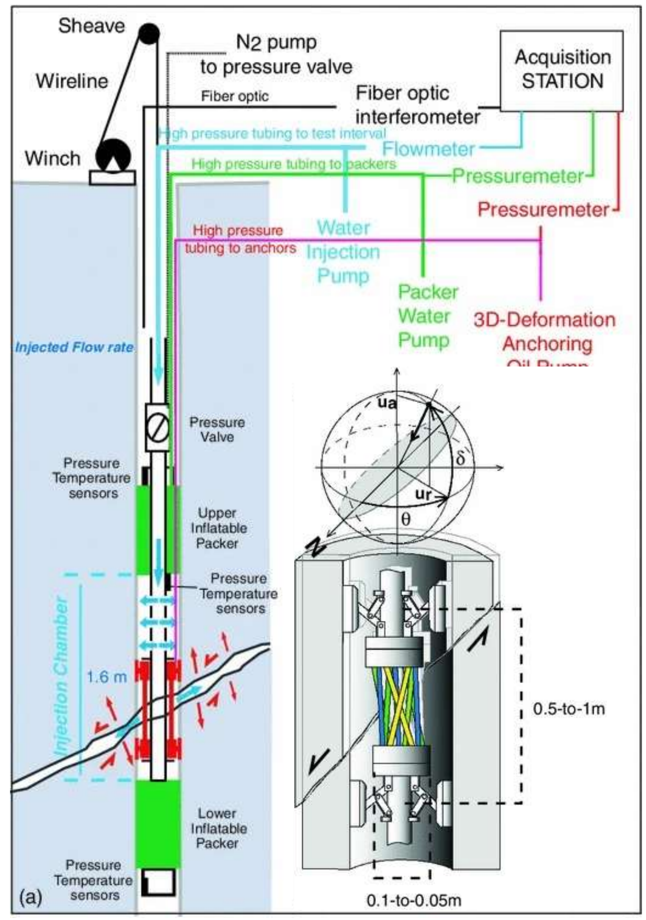


Gee et al, 2010, J. Geo. Society of Sweden 132 Pp 29 44

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 (Guglielmi et al., 2014)
- SIMFIP tool designed for direct deep downhole measurements of fracture movements based on optical fiber cage (for measurement of deformation).
- It 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

The COSC-1 deep borehole experiments were carried out at three intervals

Case I

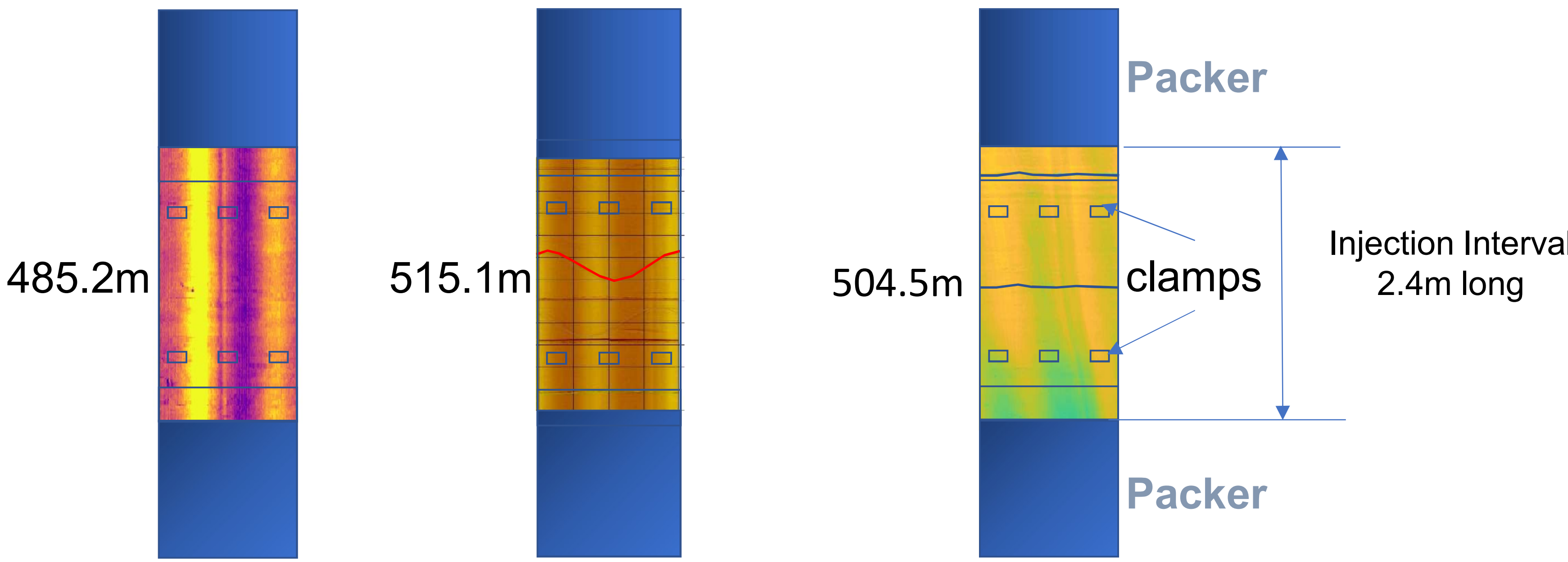
Intact Rock

Case II

Natural Non-Conductive Fracture(s)

Case III

Natural Conductive Fracture(s)



Fracture induced at higher pressure.

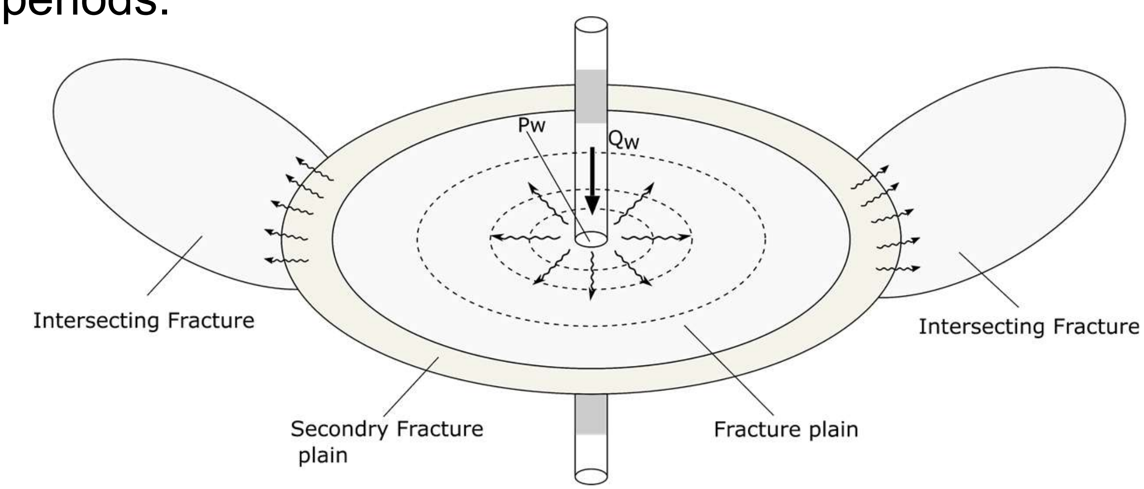
At high pressure the fracture maybe become conductive.

The aperture may become larger during the test at high pressure.

Hydraulic modeling of the SIMFIP packer tests at deep borehole

Objectives

- Develop a hydrogeological model for the SIMFIP packer tests in a deep borehole for interpretation of pressure and flow measurements for different stages of the experiments.
- In this model the mechanical effect and deformation are not included.
- Estimate parameters of induced fracture such as length, average aperture, and geometry, based on the pressure response during water injection or abstraction periods.
- A conceptual model is defined with a single horizontal fracture with variable aperture at different radius.



Based on Rutqvist et al., 1998. Water Resources Research. 34-10: 2551-2560

Model development

- We assumed the rock is not deformed during the this particular stage of time in test (no mechanical effect).
- Equations of flow in the fracture with variable apertures is solved.
- The permeability of intact rock is negligible and there is no flow in rock.
- The wellbore effect is included in the model by defining a nonlinear pressure-flow dependent function for wellbore storage.
- The wellbore storage coefficient includes the compressibility of packers, tubes, tools between packers, rock surrounding the wellbore.

Darcy's law for the fracture (1D radial)

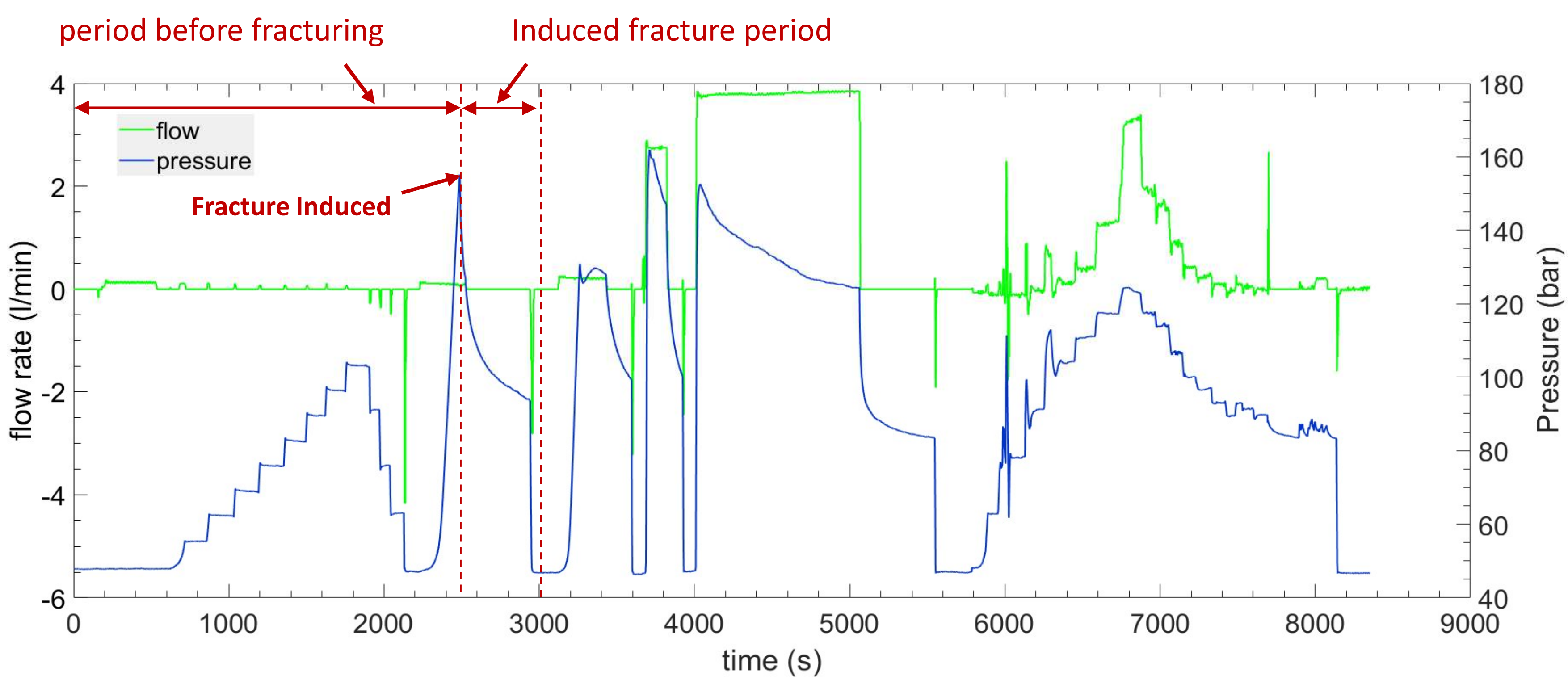
$$d_f \frac{\partial}{\partial t}(\varepsilon_f \rho) + \nabla.(d_f \rho \mathbf{u}) = d_f Q_m$$

$$d_f \frac{\partial}{\partial t}(\varepsilon_f \rho) = \rho S \frac{\partial p}{\partial t}$$

$$\mathbf{u} = -\frac{k_f}{\mu} \nabla_T p$$

ρ	Density of fluid
k_f	Permeability of fracture
d_f	Aperture of fracture
ε_f	Porosity of fracture
μ	Viscosity of fluid
$\mathbf{u}$	Velocity vector
p	Pressure
S	Storage coefficient

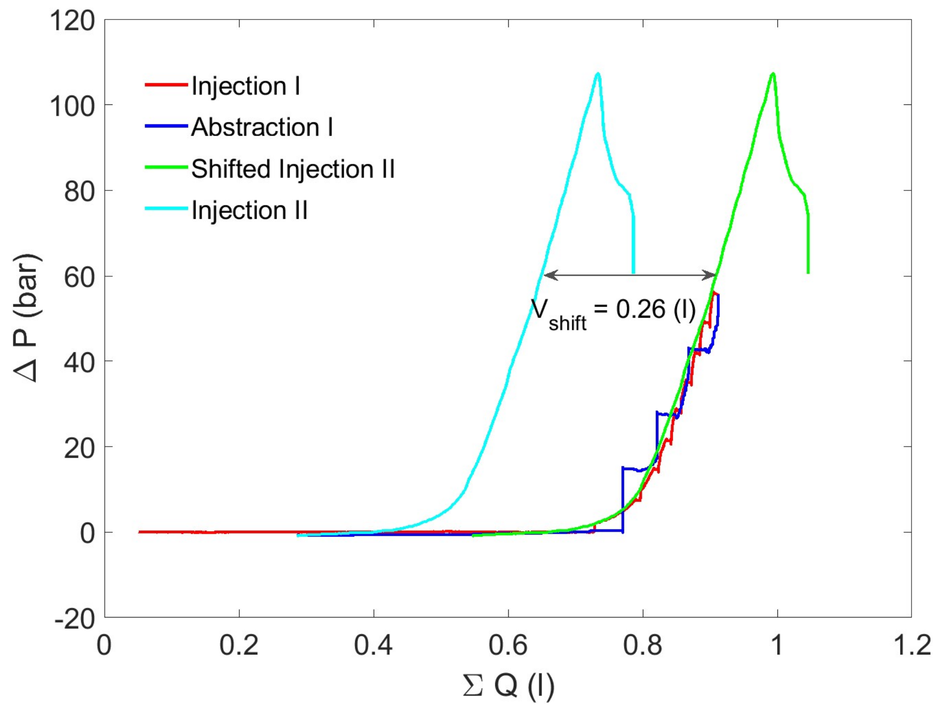
Case I- test of section without fracture initially (Intact rock)



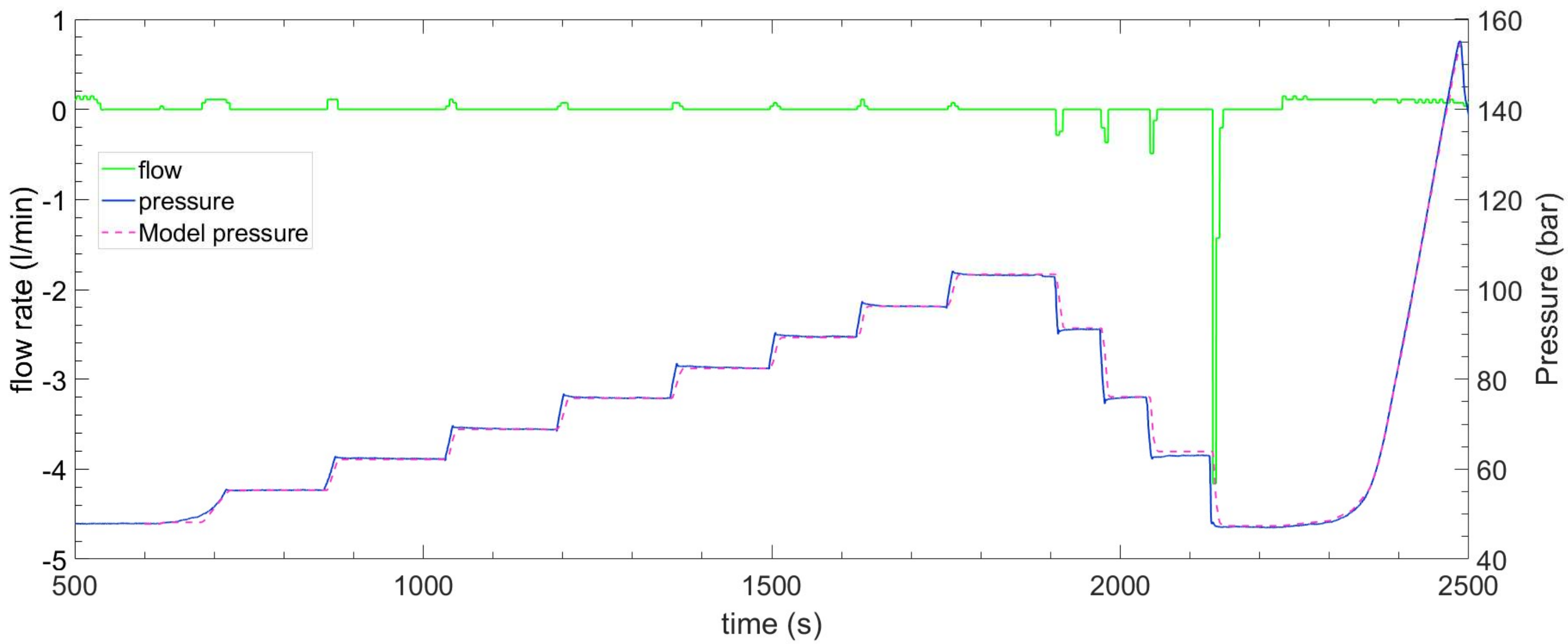
- This section initially has no fracture and the flow and pressure data of the period before fracturing are used to find the parameters of the packered borehole interval.
- Then the model is applied to estimate the generated fracture length, aperture, geometry.

Case I – ΔP versus ΣQ for three pre-fracturing time periods up to 2490 sec

- Change in pressure with cumulative flow or injected (or pumped out) volume are shown in the figure for pre-fracturing time period up to 2490 sec.
- The slope of curves in this figure gives storage coefficient (or compressibility) of the borehole between packers. It shows the wellbore compressibility has non-linear behavior.
- Initial volume of water between packered interval is the only adjustable parameter was used to match the model and field pressures.

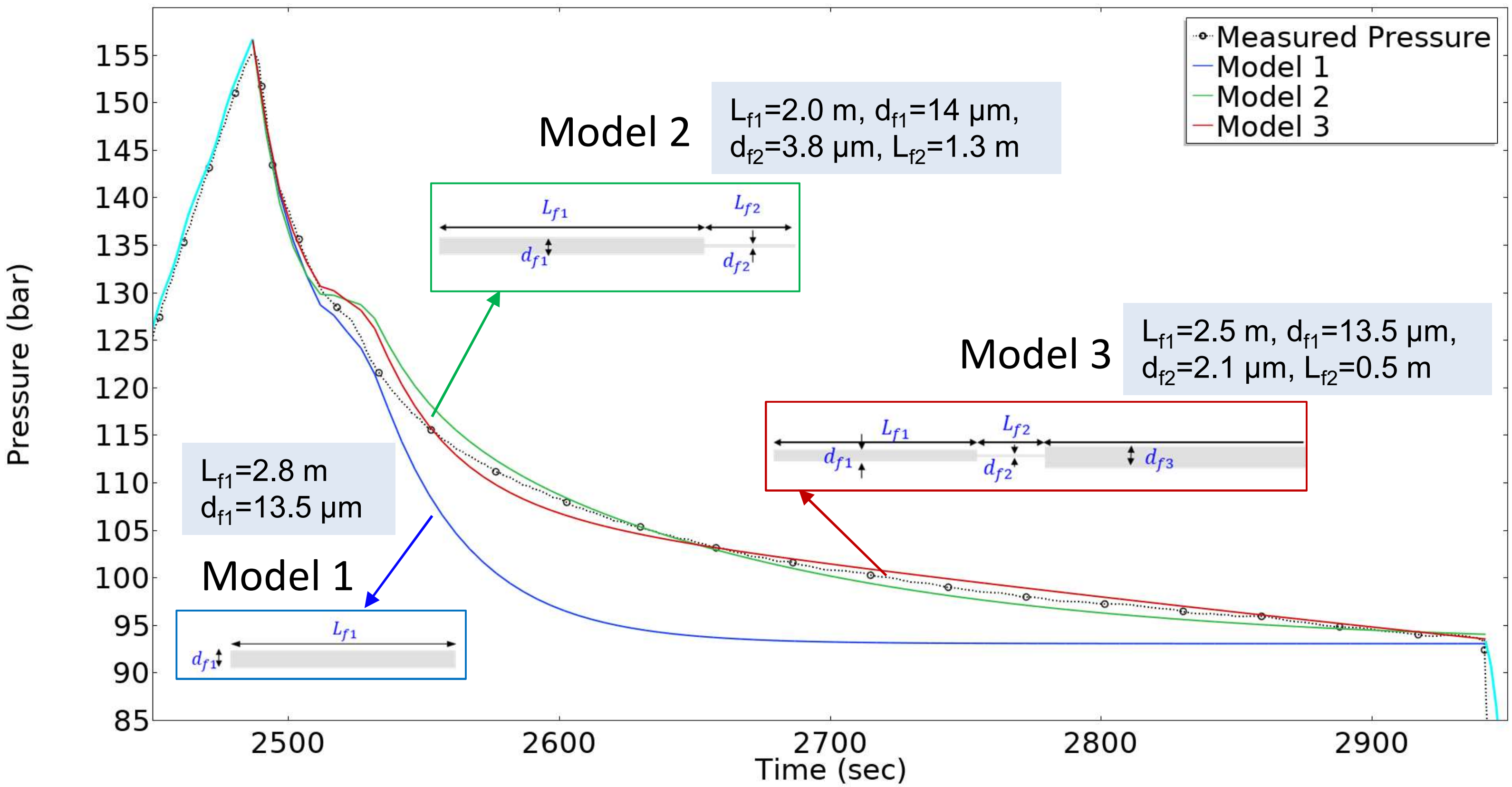


Modeling the pre-fracturing period



- The modeled pressure shows a very good agreement with measured pressure for pre-fracturing period.
- In the next step we modeled the induced fracture for period between 2490 sec and 3000 sec by using three different conceptual models.

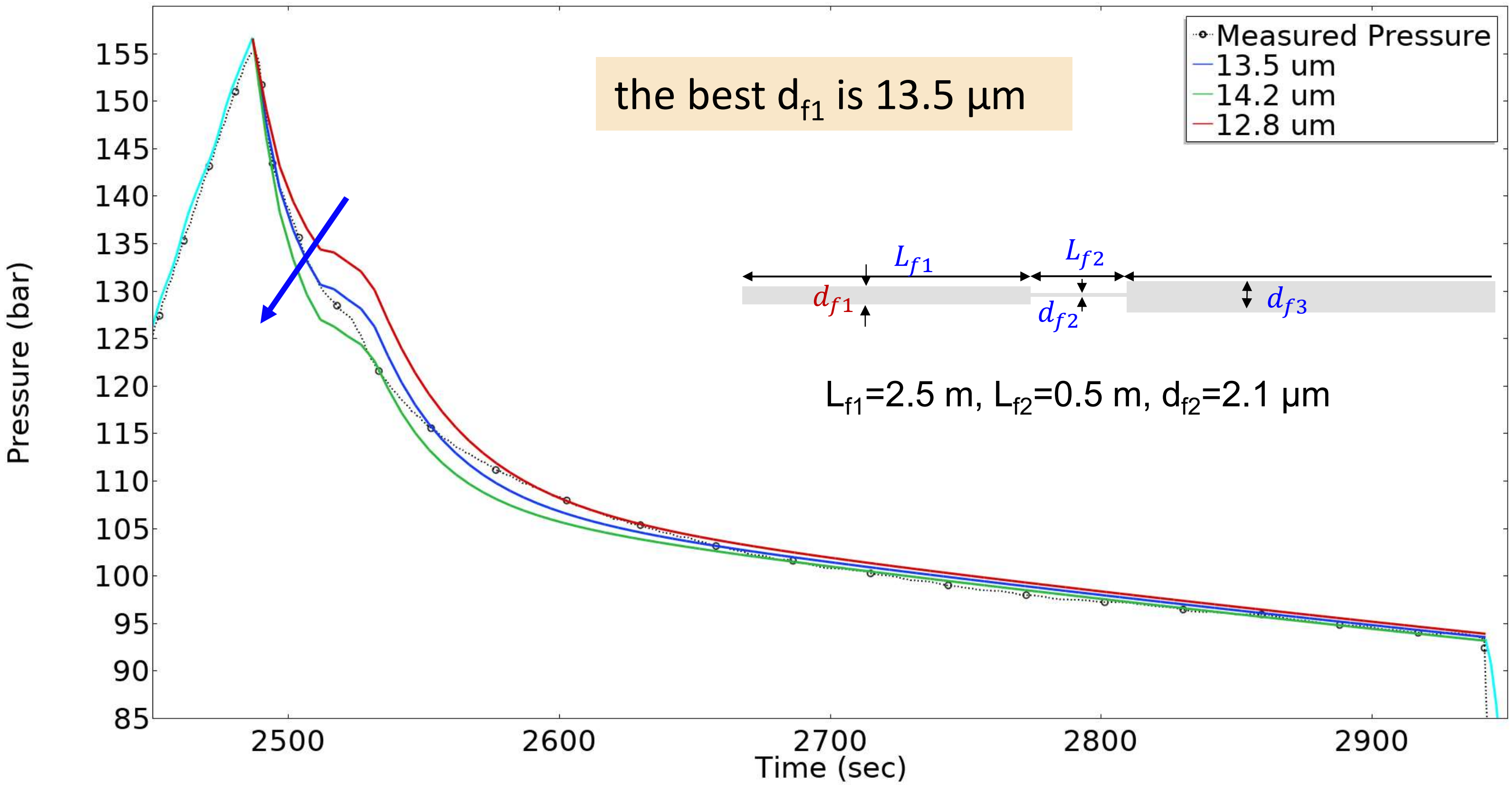
Modeling the induced fracture



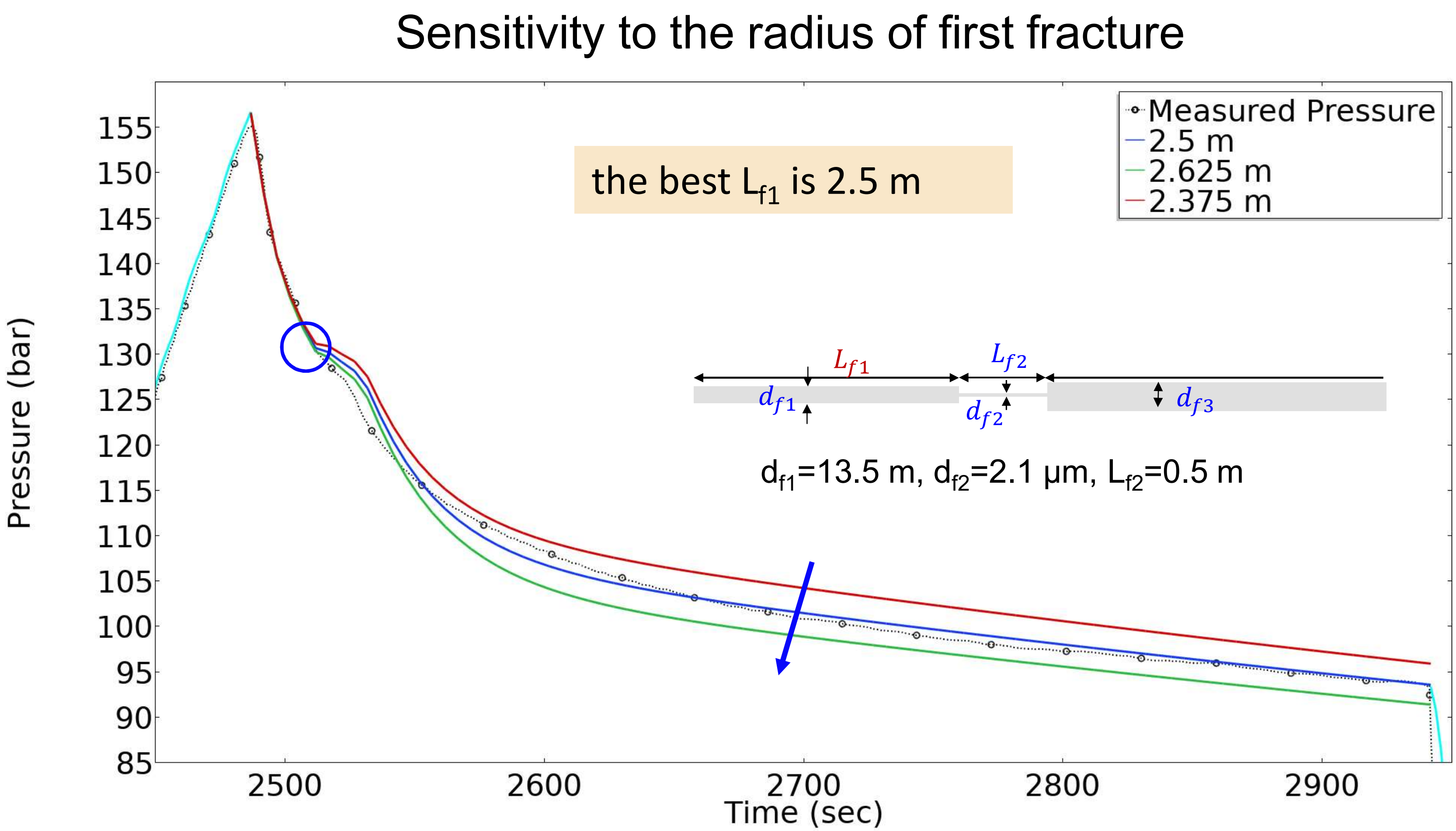
- Three conceptual models are used and the best result for each model is shown in the figure.
- Simulated pressures from Model 2 and 3 are matched better with measured pressure.
- Sensitivity analyses to each parameter are done individually for the models.

Sensitivity of Model 3 to the fracture parameters

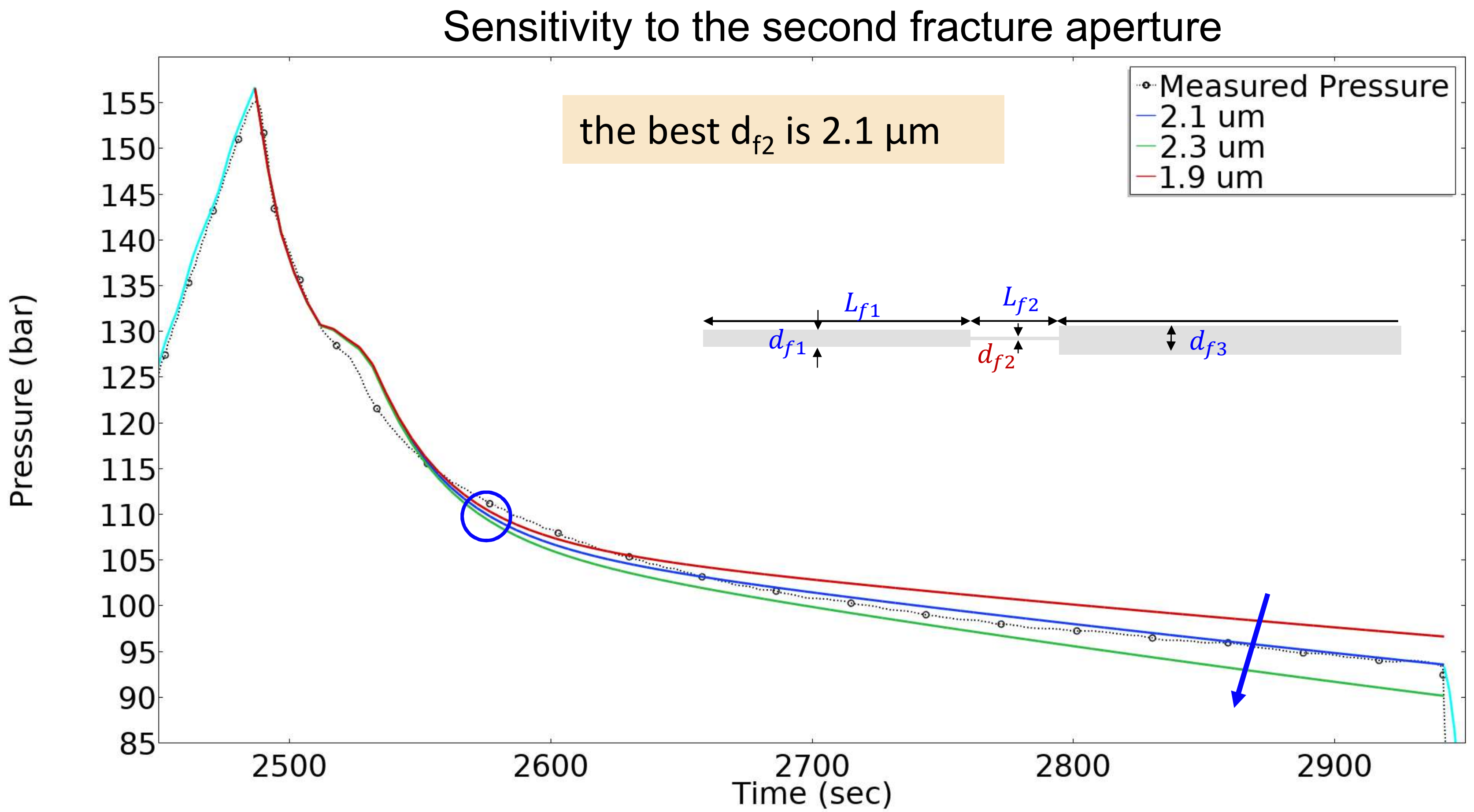
Sensitivity to the first fracture aperture



Sensitivity of Model 3 to the fracture parameters



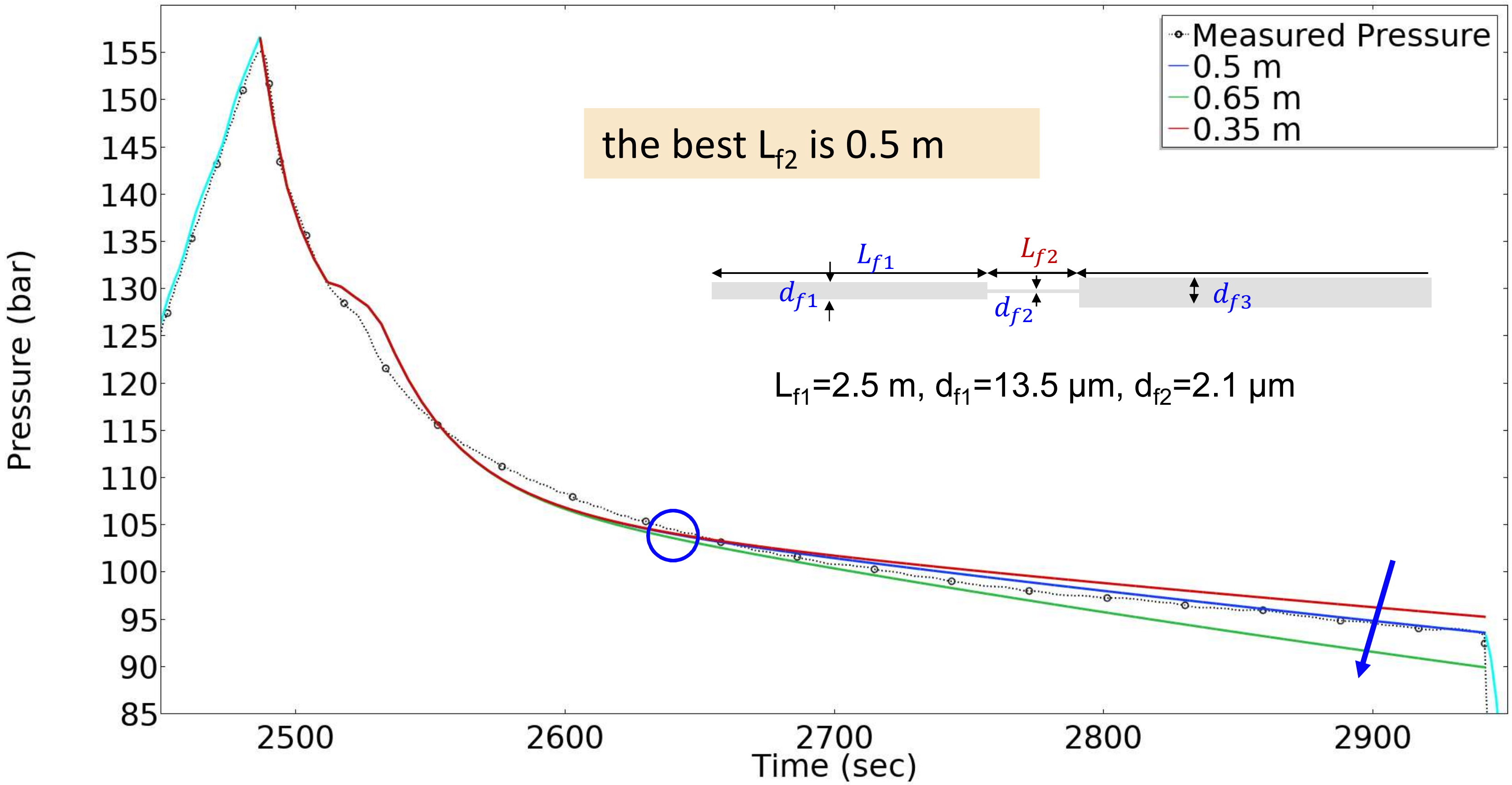
Sensitivity of Model 3 to the fracture parameters



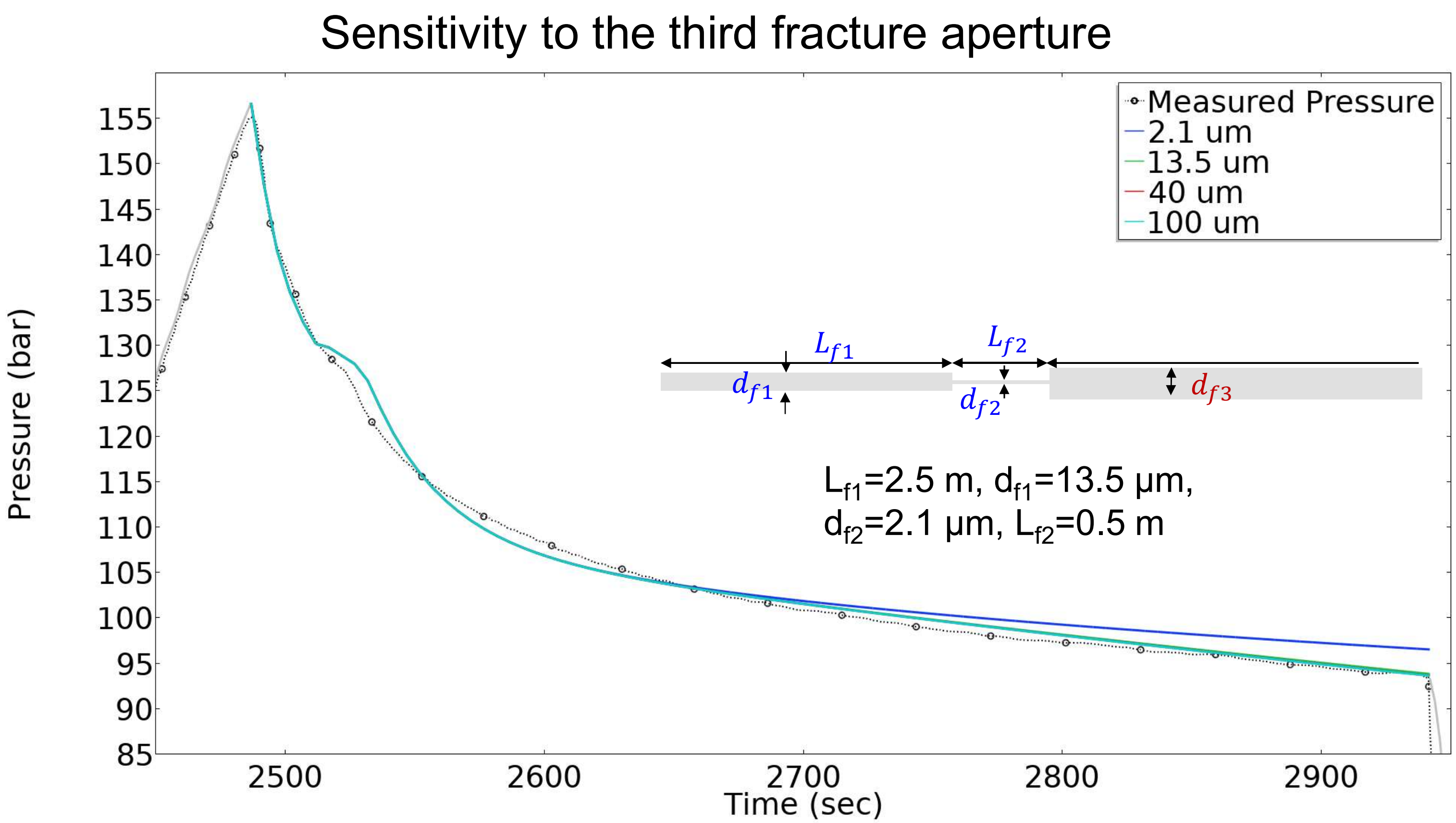
L_{f1}=2.5 m, d_{f1}=13.5 μm, L_{f2}=0.5 m,

Sensitivity of Model 3 to the fracture parameters

Sensitivity to the second fracture length



Sensitivity of Model 3 to the fracture parameters

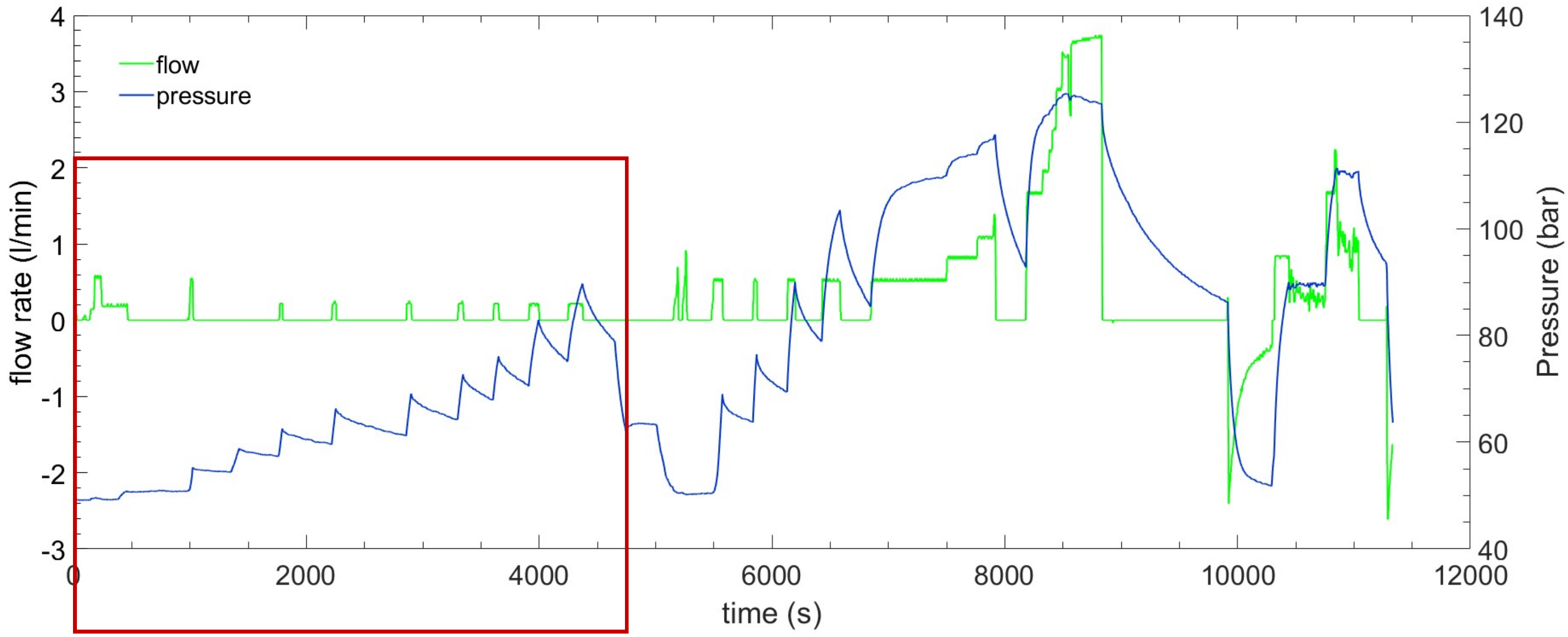


- Aperture of third fracture represents effective permeability of the flow domain beyond the second fracture.
- Note that the third fracture is assumed to extend from the second fracture to boundary of the domain.

Concluding remarks from modeling Case I pre-fracturing and after fracturing

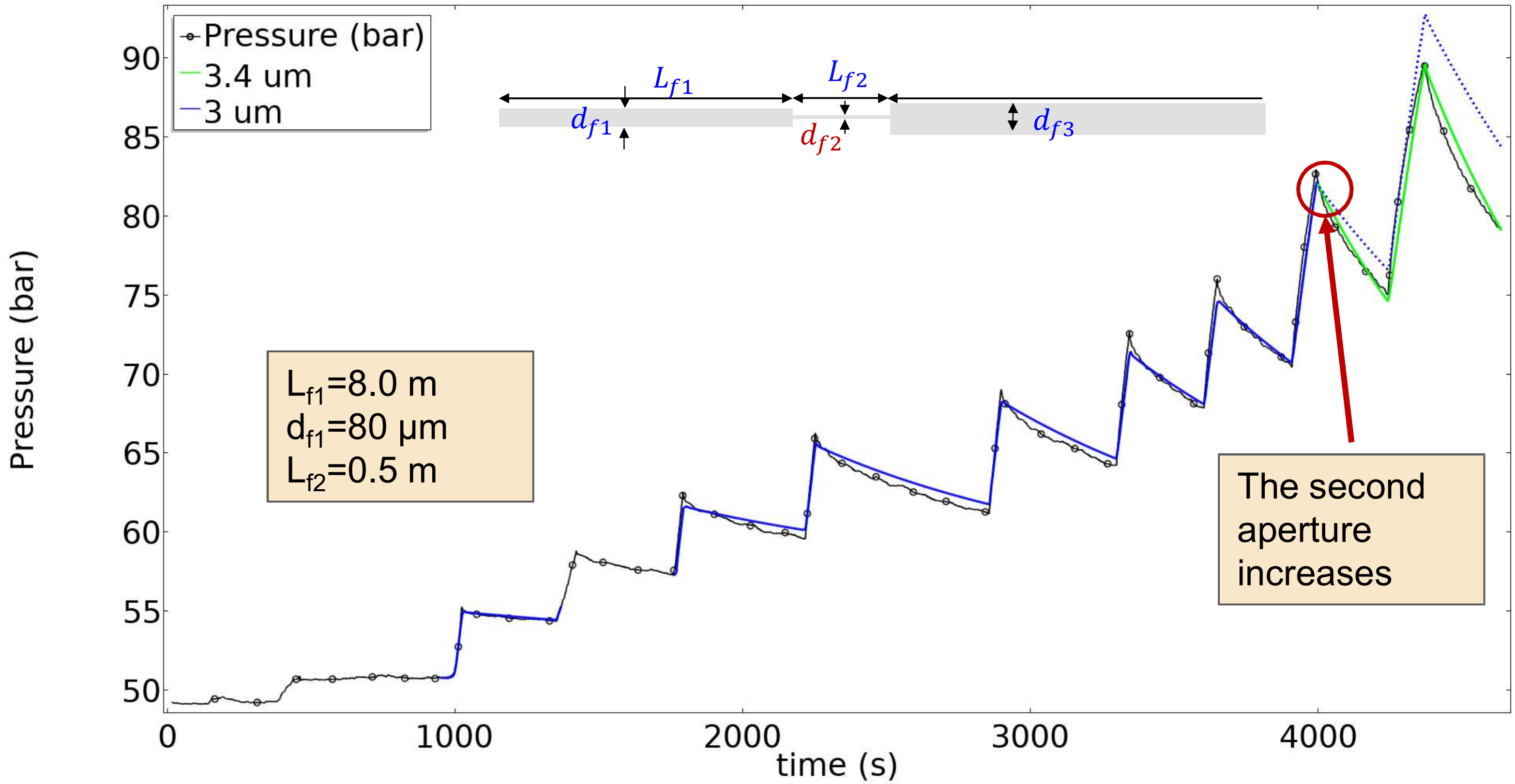
- Modelling of case I in the intact rock, prior and after fracture generation completed.
- The time-varying storage coefficient of wellbore (with packers and tubing, etc.) as measured was used (some hysteresis as well as initial delay in pressure increase was observed)
- The model with small aperture at the ending of the induced fracture can explain the pressure response during the test. (Model 2 and 3)
- Model 2 and Model 3 are different only in the boundary of the second fracture.
- In Model 2, the second fracture ends with closed boundary, but in Model 3, the second fracture is open to a network of fractures (represented by “third fracture”) which extends to the far boundary of the domain at constant pressure.

Case III- Analysis of the section with 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 III- Modeling results for the section with conductive fracture



- The modeling result indicates that at pressures above 80 bars the fracture parameters need to be changed.
- Based on the conceptual model, the narrow section [fracture 2] needs to be increased from 3.0 μm to 3.4 μm.

Conclusions

- Modeling of Case III, the section with conductive fracture completed for the initial low injection pressure period.
- The modeling results indicate that at pressures above 80 bars the fracture conductivity increases, and the aperture of the second fracture needs to be larger.
- The work is in progress for Case II (the section with non-conductive fracture) and Case III (the section with conductive fracture).
- After the analysis of the flow and pressure is completed, the results would be integrated with a study of simultaneous analysis of flow, pressure and deformation data [the latter study is also under way]

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Thank you

The Geological Survey of Sweden and US Department of Energy are gratefully acknowledged for the funding of this work