ZoDrEx

Zonal Isolation, Drilling and Exploitation of EGS Projects

Reservoir stimulation tests in the Bedretto Lab (January 15th - February 5th 2020)

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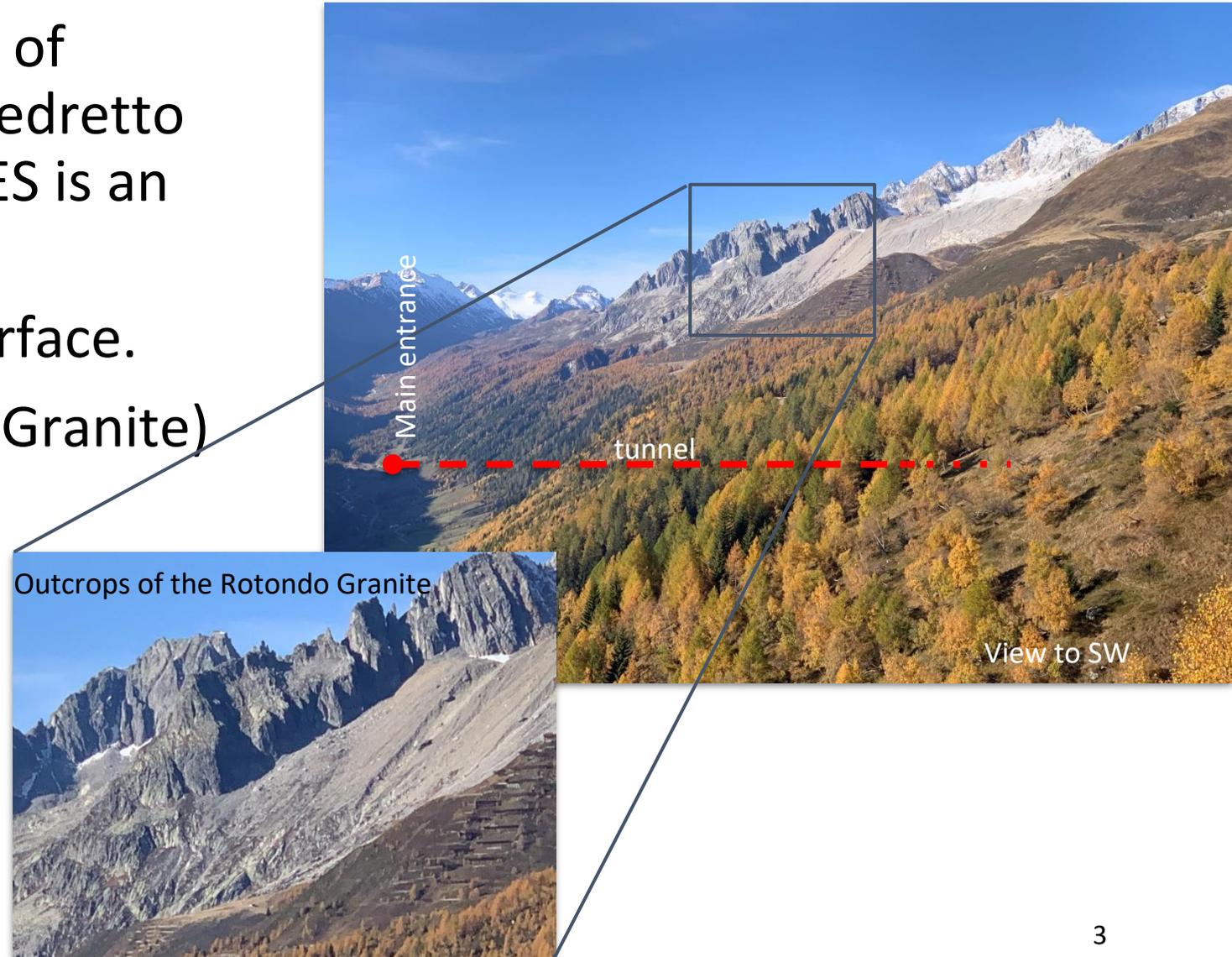
With contributions from X. Ma, H. Krietsch, A. Shakas and M. Hertrich (ETH, SCCER-SoE)
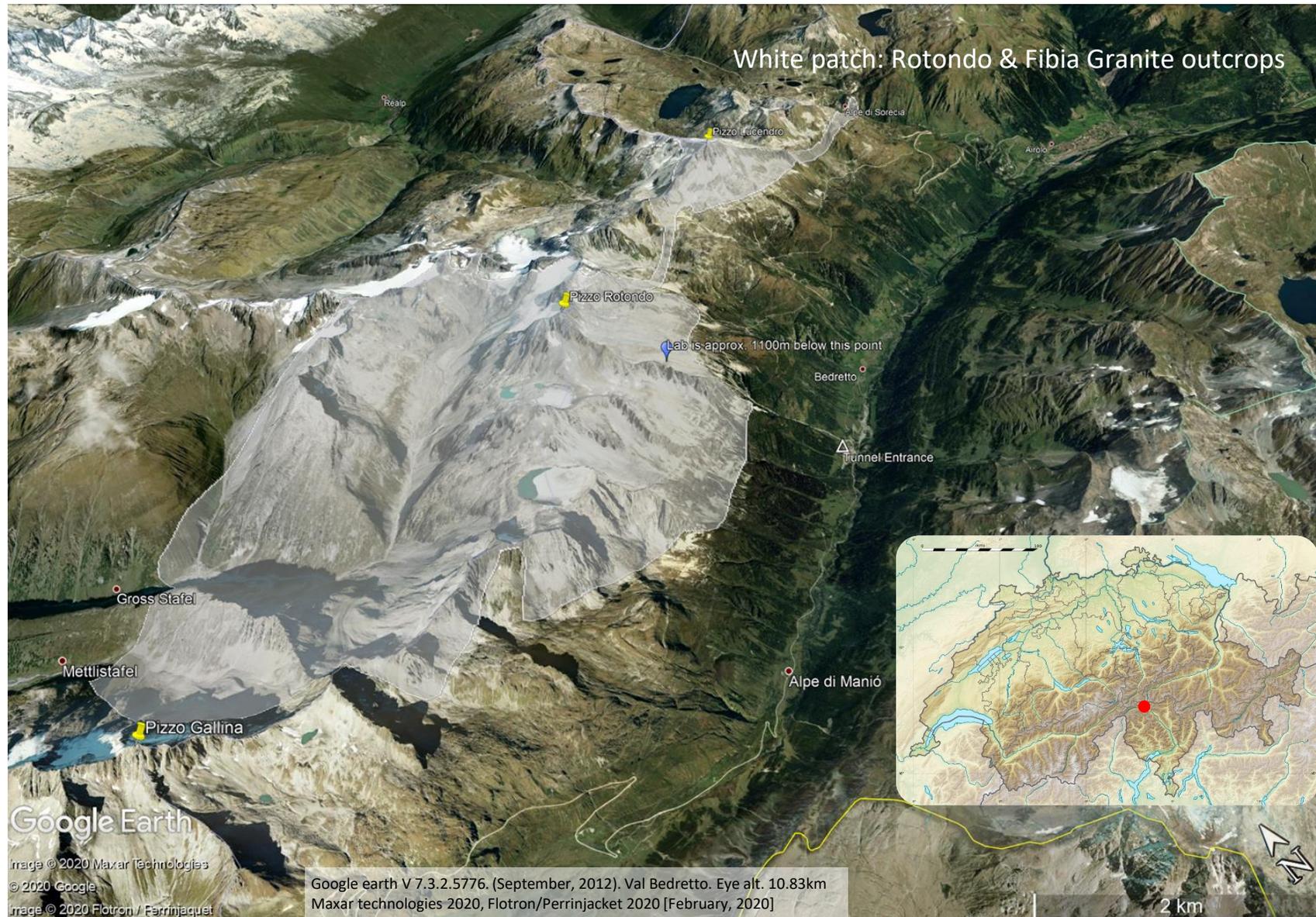
Overview Bedretto Lab

The Bedretto Underground Lab (I/III)

- ETH (Swiss Federal Institute of Technology) operates the Bedretto underground laboratory. GES is an industry partner.

- 1100 m depth below the surface.

- Hosted in granite (Rotondo Granite)

http://www.bedrettolab.ethz.ch/home/

Main entrance

tunnel

View to SW

Outcrops of the Rotondo Granite

The Bedretto Underground Lab (II/III)

White patch: Rotondo & Fibia Granite outcrops

Google earth V 7.3.2.5776. (September, 2012). Val Bedretto. Eye alt. 10.83km
Maxar technologies 2020, Flotron/Perrinjacket 2020 [February, 2020]

- The southern entrance of the Bedretto lab is located in the Val Bedretto (Canton of Ticino, Switzerland) at approx. 10km from the town of Airolo.

- The Lab (*sensu stricto*) is located in a 100m long, enlarged section of the tunnel at 2 km from the southern entrance.

- The overburden at the lab emplacement is approx. 1100m

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The Bedretto Lab - Regional Geological context

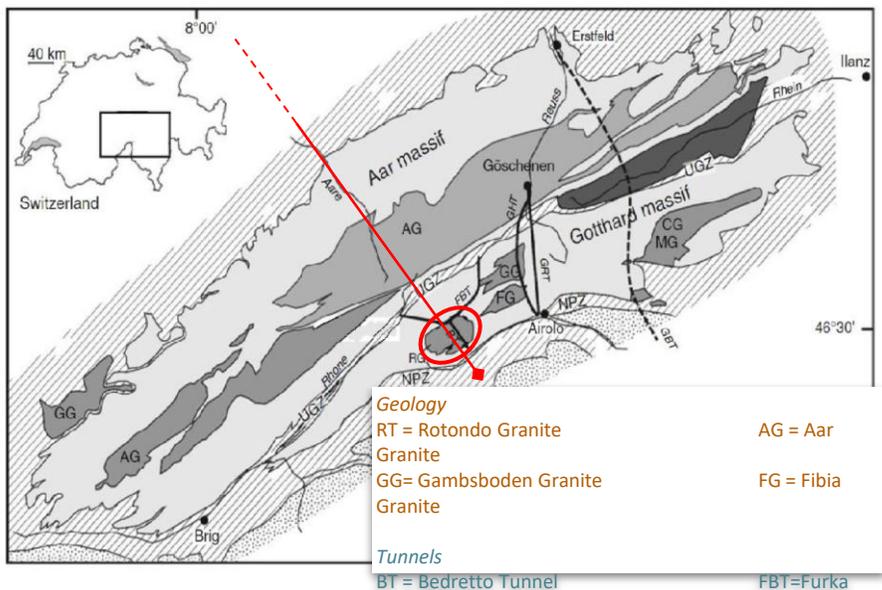
(a) Carboniferous magmatism
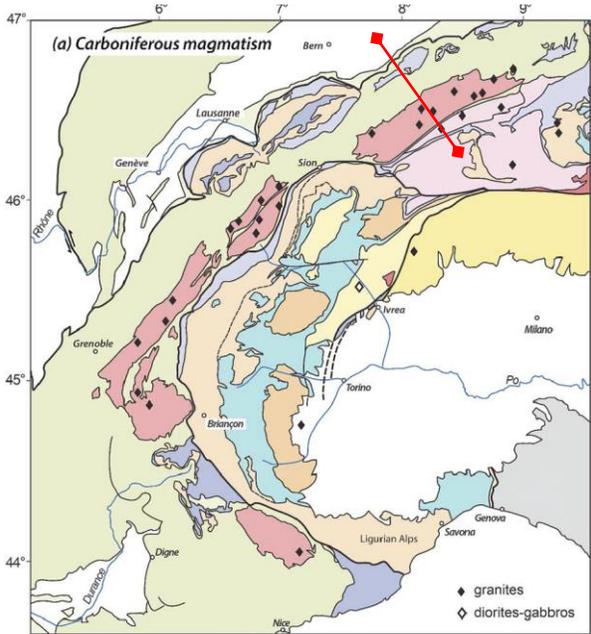
Ballevre et al. (2018)

External Massifs (dark pink) = remnants of old (pre-Alpine) rocks
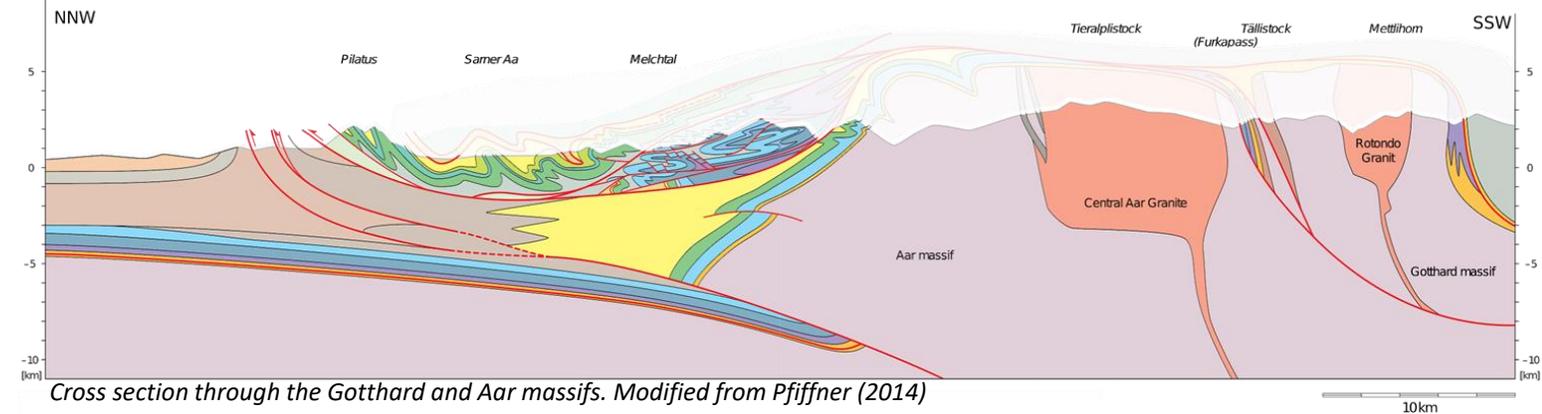
Granitoids (black losanges) = Intrusive bodies emplaced at the end of the Variscan Orogeny (approx. 300 Ma ago)

- Extensive magmatism with granite emplacement during Carboniferous and Permian.

- The Rotondo Granite is one of those magmatic bodies.

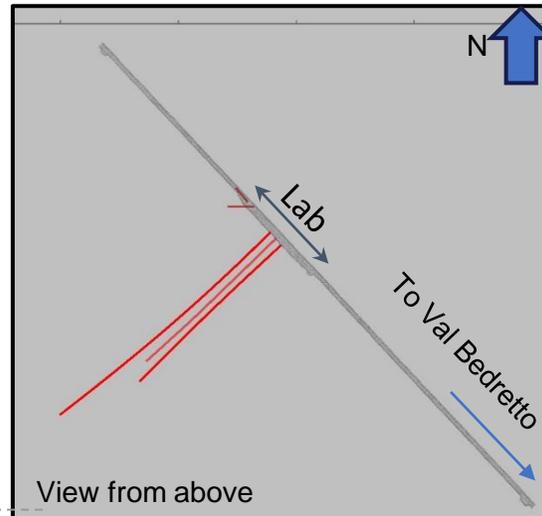- The Rotondo Granite, as part of the Gotthard massif, suffered compression and uplift during the Alpine Orogeny.

After Labhart et al. (1999)

Geology
RT = Rotondo Granite   AG = Aar
Granite
GG= Gambsboden Granite   FG = Fibia
Granite

Tunnels
BT = Bedretto Tunnel   FBT=Furka
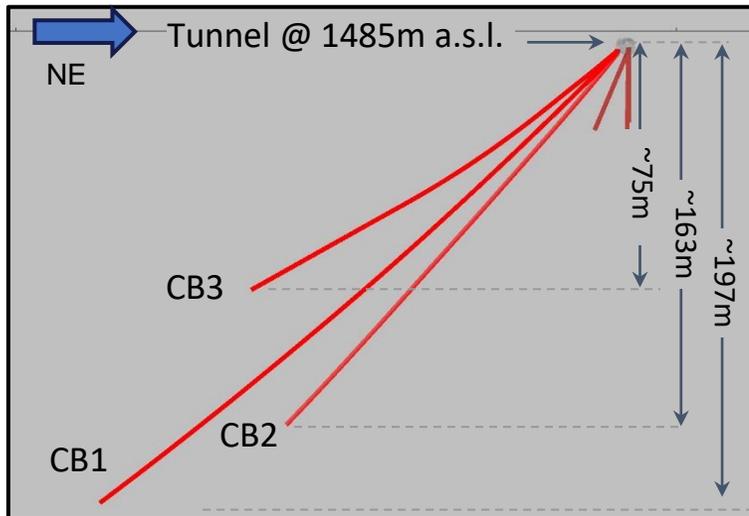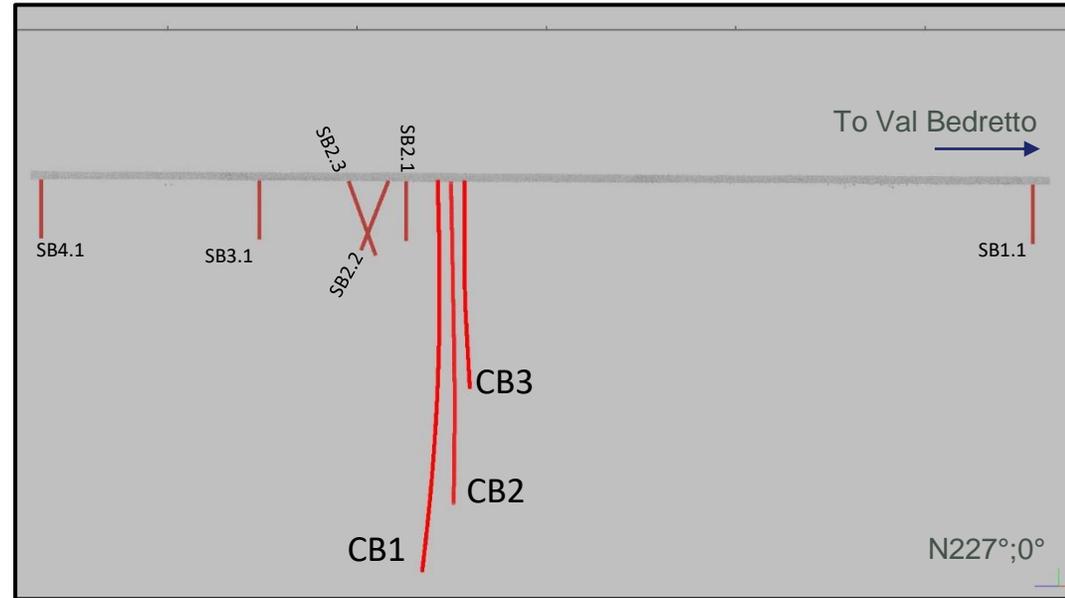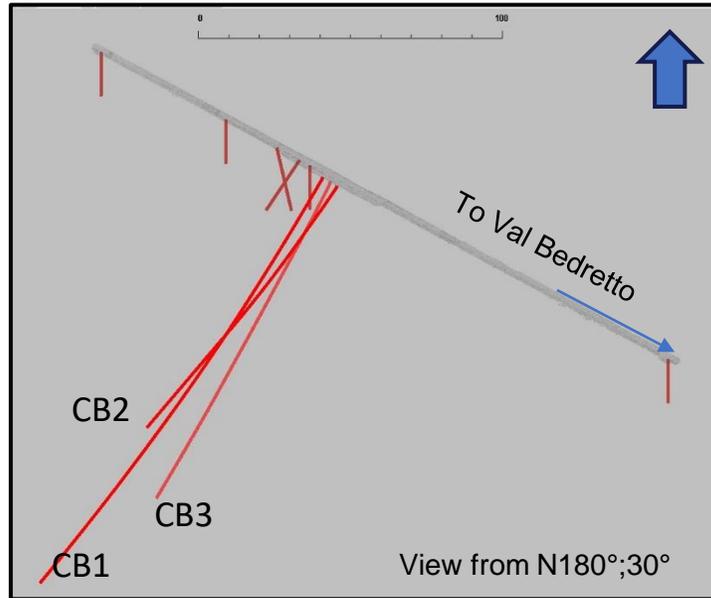

Cross section through the Gotthard and Aar massifs. Modified from Pfiffner (2014)

The Bedretto Underground Lab (III/III)

View from N180°;30°

To Val Bedretto

CB2
CB3
CB1

To Val Bedretto

SB4.1   SB3.1   SB2.3   SB2.1   SB2.2   SB1.1

CB3
CB2
CB1

N227°;0°

Tunnel @ 1485m a.s.l.

NE

CB3
CB1   CB2

~75m   ~163m   ~197m

View from southern entrance (N137°;0°)

N

Lab

To Val Bedretto

View from above
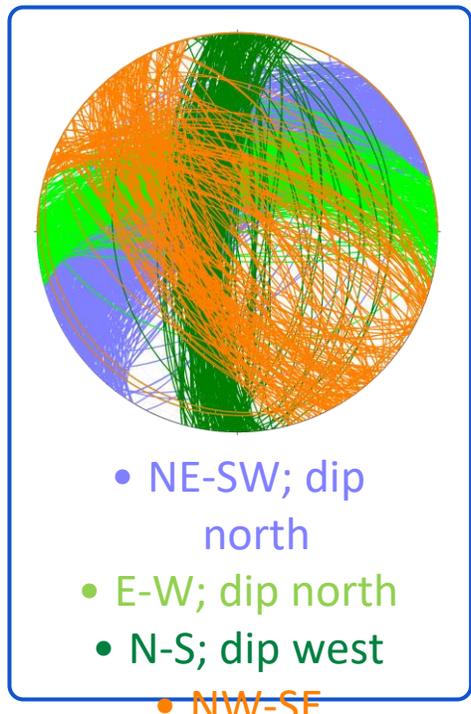
- Lab = 100 m long enlarged gallery in the tunnel.
- 6 short boreholes (30-40m):
  - SB1.1; SB2.1; SB2.2; SB2.3; SB3.1; SB4.1
- 3 long boreholes (190-300mMD):
  - CB1; CB2; CB3

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Bedretto Lab - Structure

- Structural characterisation from core and image logging.
- Identification of intact/fractured rock and fault zones.

- NE-SW; dip north
- E-W; dip north
- N-S; dip west
- NW-SE
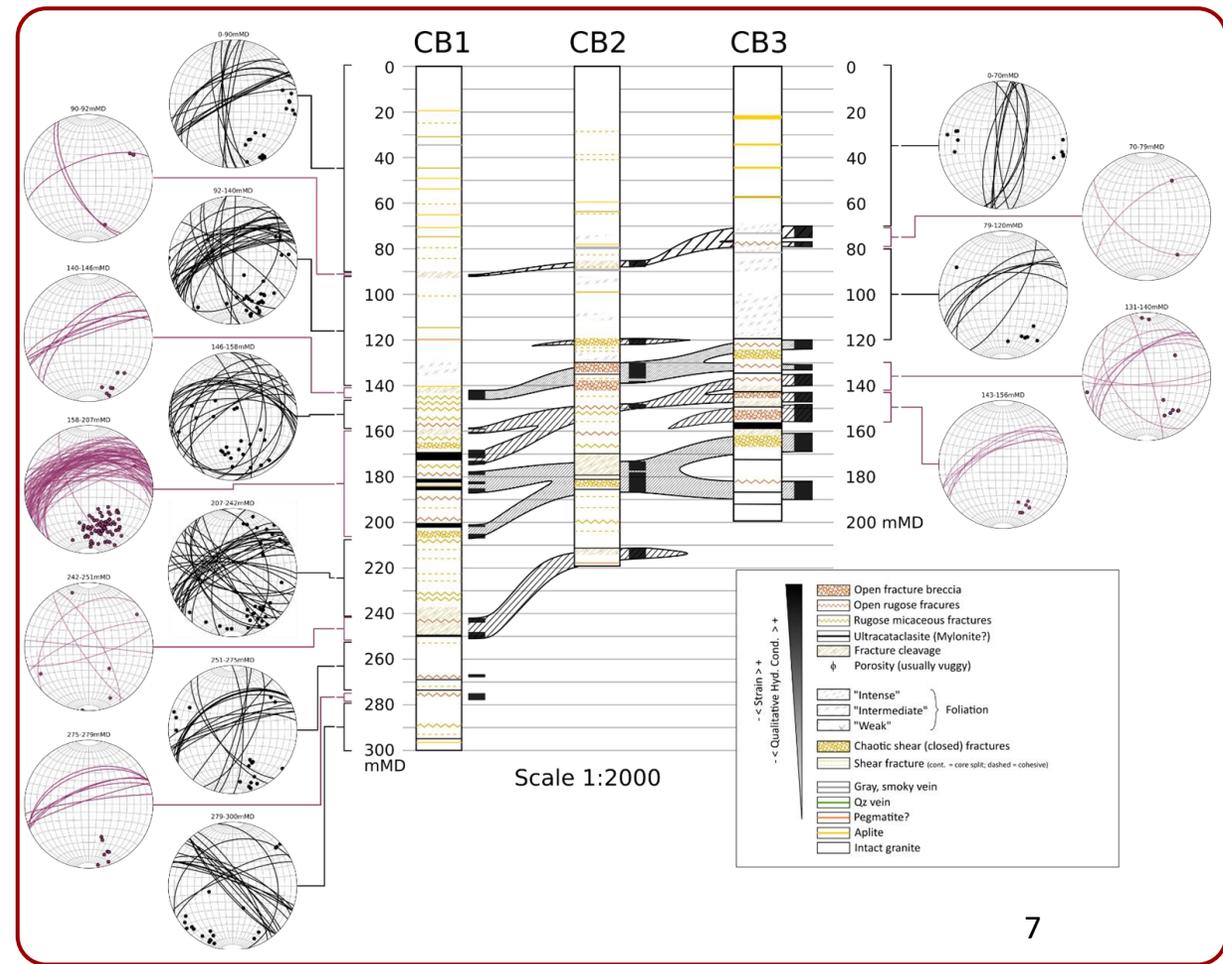
Stress

- Orientations and magnitudes from minifrac tests in short wells and CB1. (Ma et al. 2019 and ETH unpublished work)

σ1:
strike ≅ N0°
dip ≅ 90°

σ2:
strike ≅ N100°
dip ≅ 0°

σ3:
strike ≅ N190°
dip ≅ 0°

P_p = 5 MPa
μ = 0.6, 0.85

CB1
Pressure [MPa]

ETH, unpublished
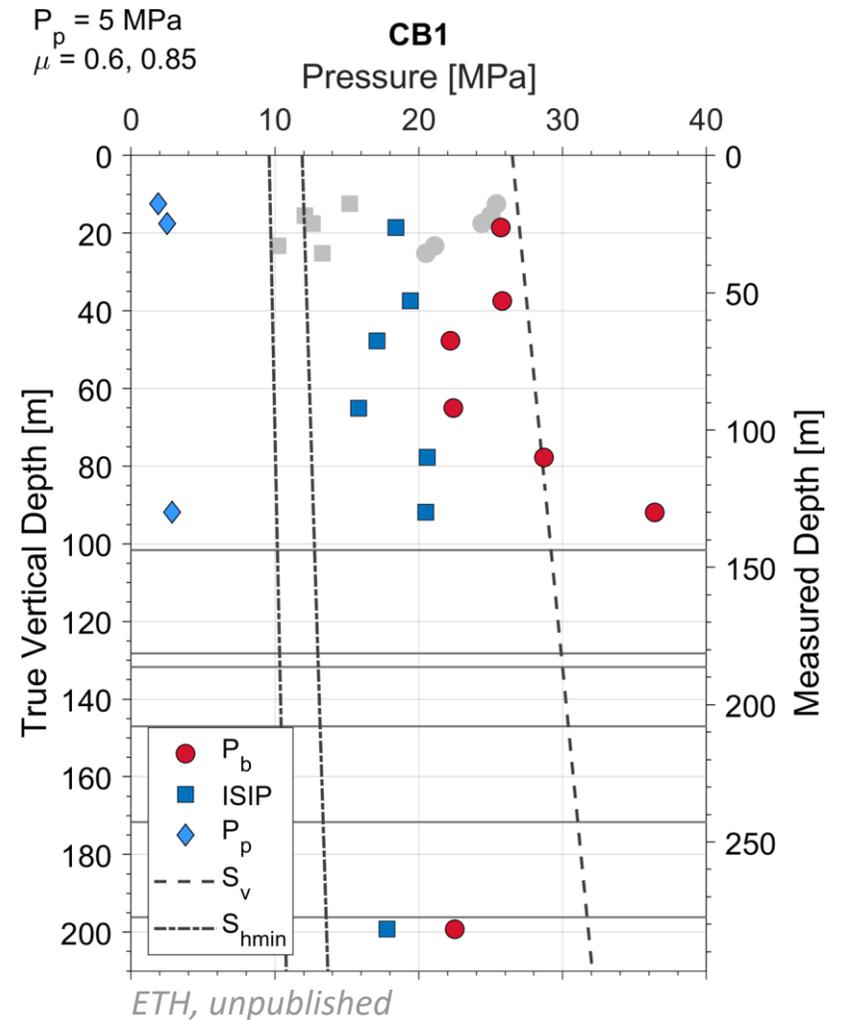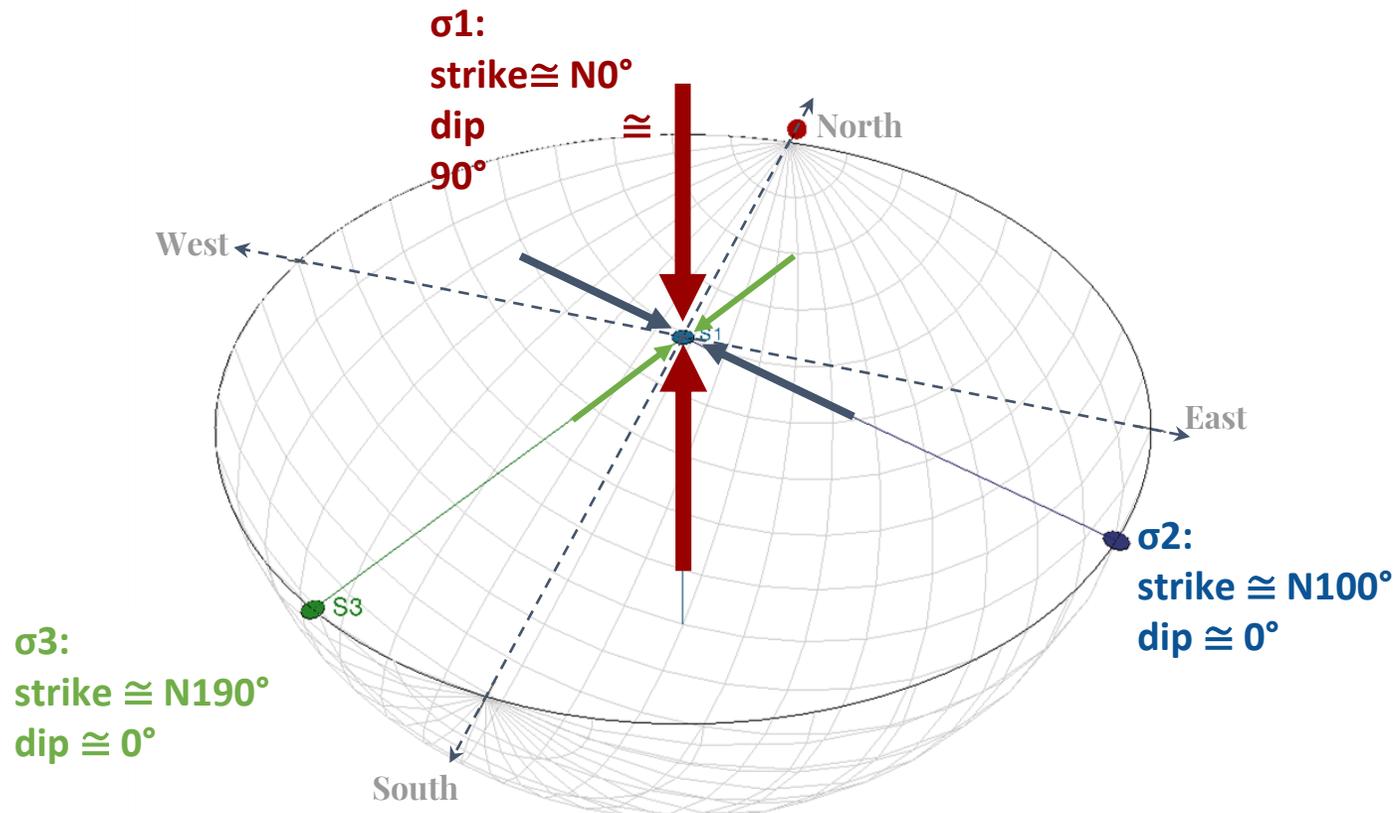
Hydrotests previous to test stimulation

- Twelve intervals were tested to estimate hydraulic properties.

- Dual-packer tests. Inter-packer spacing of 8.7m.

- T of flowing fractures 1E-8 to 5E-7 m2/s comparable to Swiss crystalline basement values (Basel, Nagra boreholes)
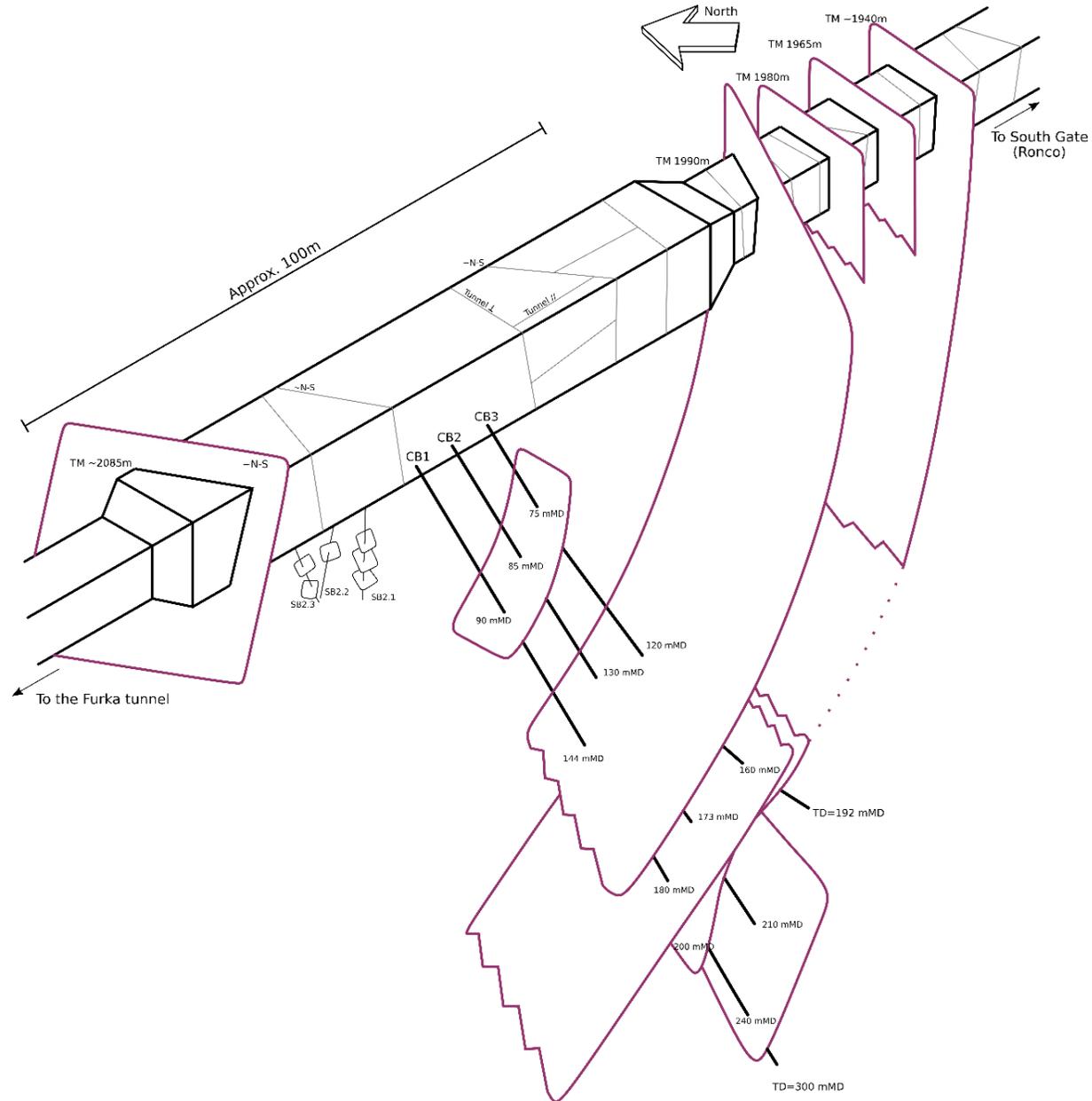
Bedretto & DESTRESS

Bedretto in DESTRESS

- Bedretto = Fall-back option that replaces Haute-Sorne.

- Reservoir creation experiment 2019/2020 led by GES at a smaller scale in Bedretto underground research lab

- Aims:
  - Demonstration of multi-stage stimulation concept to increase energy production and to minimize induced seismicity.

- Planning:
  - **January-February 2020:** Test stimulation
    - Injection in CB1 with dual packers and seismic monitoring from CB2 and CB3.
  - **Q2 2020:** Long borehole drilling.
  - **Q3 2020:** Multistage stimulation

Bedretto vs. Full scale deep EGS

Haute Sorne
Multistage stimulation concept for deep project

R≈300m
spacing of stages≈50m

300m

4000m

distance≈200-300m
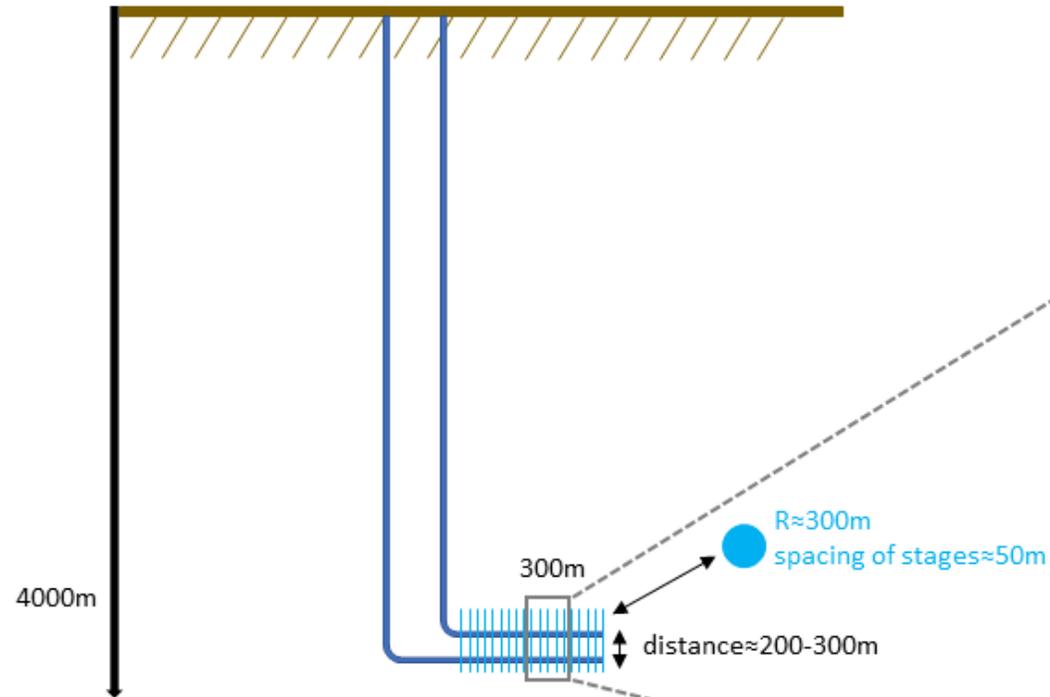
Bedretto
Demonstration of concept with dimensions of deep project
Multistage stimulation (MS) vs open hole stimulation (OHS)

High resolution monitoring

Q_{MS1} Q_{MS2} Q_{OHS}

distance 30-60m

R≈50-200m

Q_{MSn-1} Q_{MSn}

distance 50-150m

High resolution monitoring

Demonstration of concept:

$\sum Q_{MSi} \gg Q_{OHS}$

$\sum SeismicRisk_{MSi} \ll SeismicRisk_{OHS}$
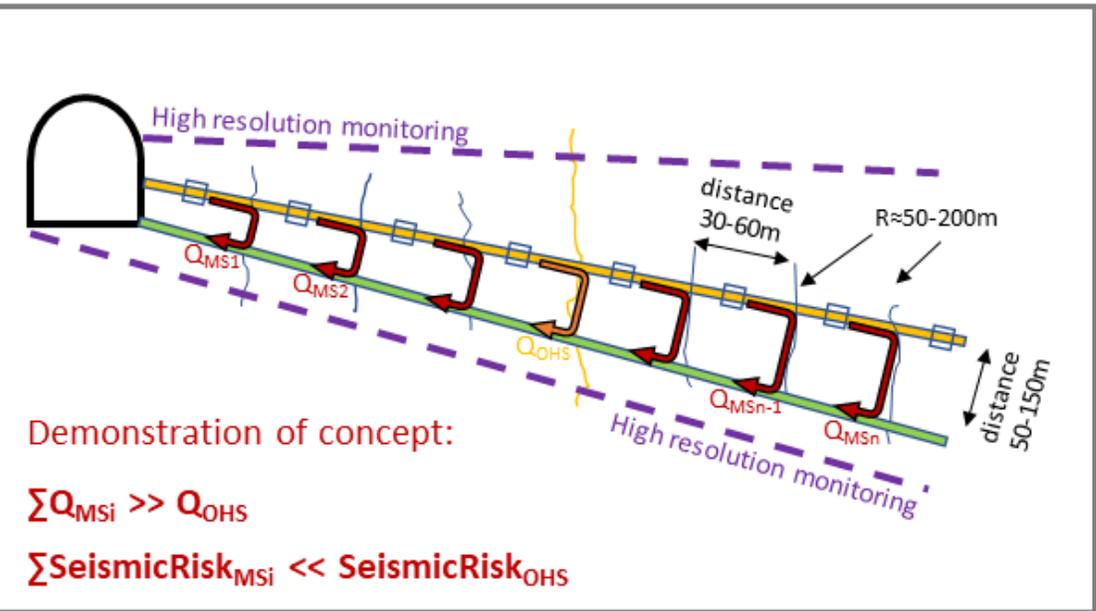
Test Stimulation

Test Stimulation - General Concept

- General Concept:
    - To stimulate pre-existing structures in the CB1 borehole.
    - Individual intervals are isolated via a dual packer system.
    - Seismic monitoring from 2 adjacent boreholes (CB2 and CB3).

Test Stimulation - Motivation

- Motivation:
  - The test stimulation is needed as a basis for further planning.
  - The outcome delivers important data for the further planning and investments by answering the following questions
    - Is the model concept the right one?
      - How does the rock behave, do we shear or jack the formation ?
      - Are we able to (permanently) increase flow ?
    - Can we stimulate in a controlled manner?
      - Can we detect and locate induced earthquakes?
      - Can we calibrate our models to forecast seismicity?
    - Are the planned boreholes at the right spot?
      - Where does seismicity propagate to?

Test Stimulation - Implementation

- Previous Analyses:
  - Core & image logging.
  - Hydraulic tests on CB1.

- Choice of stimulation pressures:

  - Prognosis based on structural orientations and available stress scenario.

  - Induced seismicity hazard and seismic risk study by ETH (Gischig et al., 2019).

- Design of TSL and ATLS and associated reaction & communication plan.

  - Based on the Gischig et al. study mentioned above.

- Selection of intervals and packer spacing for stimulation on CB1.

- Choice of optimal depths for monitoring system in CB2 and CB3.

Selection of intervals

Stimulations candidates

- 6 parameters were used to choose the candidate structures for stimulation:

    1) How favourably oriented is the structure for shear reactivation?

    2) Is there any aperture associated to the structure (in core and ATV)?

    3) Is there any vuggy porosity in or around the structure?

    4) Does the structure seem to be isolated from others? (qualitative hypothesis)

    5) What was the flow in previous hydraulic tests?

    6) Are there good conditions for packers placement above and below?

Chosen intervals

- Five intervals were isolated and stimulated
  - Two intervals 2.7m long
  - Three intervals 9.9m long

Interval designation *	Interval length (m)	Top	Bottom	Favourably oriented structure	"Open" structure	Vuggy Porosity	Isolated structure	Flow (l/min)	Packer seats on intact rock
STIM-250	2.7	249	251.7	✔	X	X	X	0.008	X
STIM-267	2.7	265.7	268.4	✔	✔	✔	X	0.01	✔
STIM-269	9.9	264.0	273.9	✔	✔	✔	X	0.01	X
STIM-292	2.7	290.7	293.4	✔	✔	X	✔	**	✔
STIM-295	9.9	288.5	298.4	✔	✔	X	✔	??	✔
HF-298	0.7	297.8	298.5						

*   STIM = Main stimulation;

     HF = Minifrac test carried out by ETH before DESTRESS stimulation (for stress determination)

**   = Not possible to measure

# Chosen intervals - Examples of targeted structures

STIM-267

- A couple of rugose fractures very close to each other.
- They are part of a segment described in the core as a fault zone.
- Orientation is favourable for shear reactivation (strike=253°, dip=85°).
- Previous hydraulic tests yielded a flow rate of 0.01 l/sec.
- Vuggy porosity can be observed around these structures which might facilitate the injection.

290

292.5
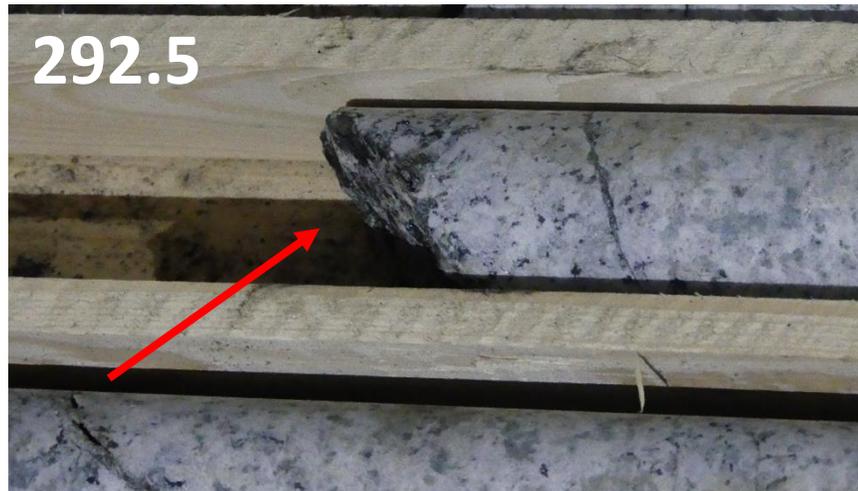
- Closed rugose structure, well oriented for shear reactivation (strike=330°, dip=75°) but not too open.
- No previous hydraulic tests were run on this structure.
- Well imaged in radar data which means it has some water saturation.
- Given its characteristics, it might be challenging to inject fluid in it.

GPR of selected stimulation intervals

250 MHz Reflection GPR

ETH, unpublished
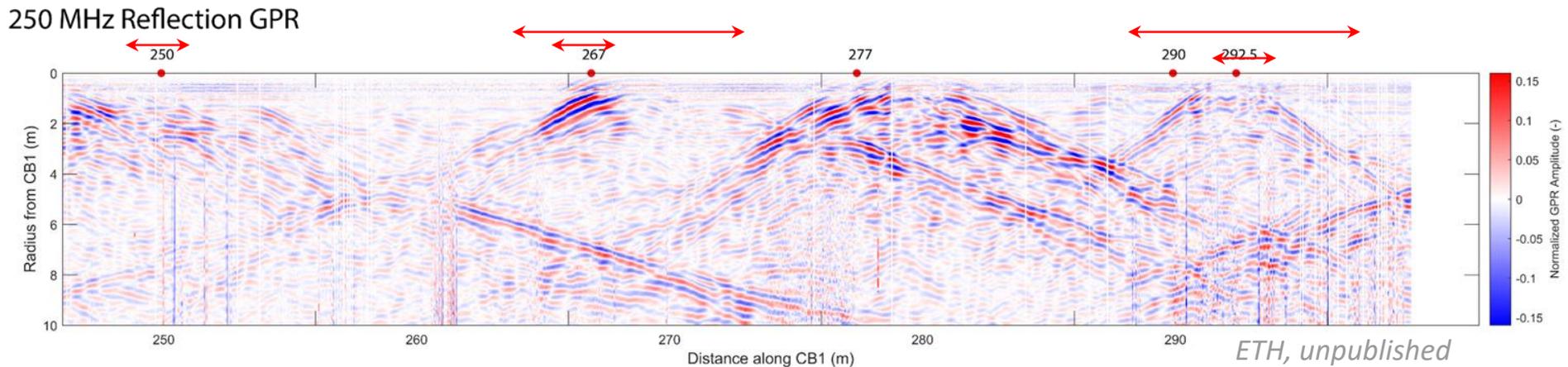
- Intervals around 267 and 290m show structures intersecting the well.
- High amplitudes near the well at 250m indicate the presence of nearby structures.

Seismic monitoring

Seismic Network

- Stimulation hole CB1 : two one-component sensors were placed on top of the upper packer

- Monitoring wells CB2 & 3: four 3-component geophones (4x 10m intervals) in places of low breakouts

- DAS in CB3 above last geophone to tunnel

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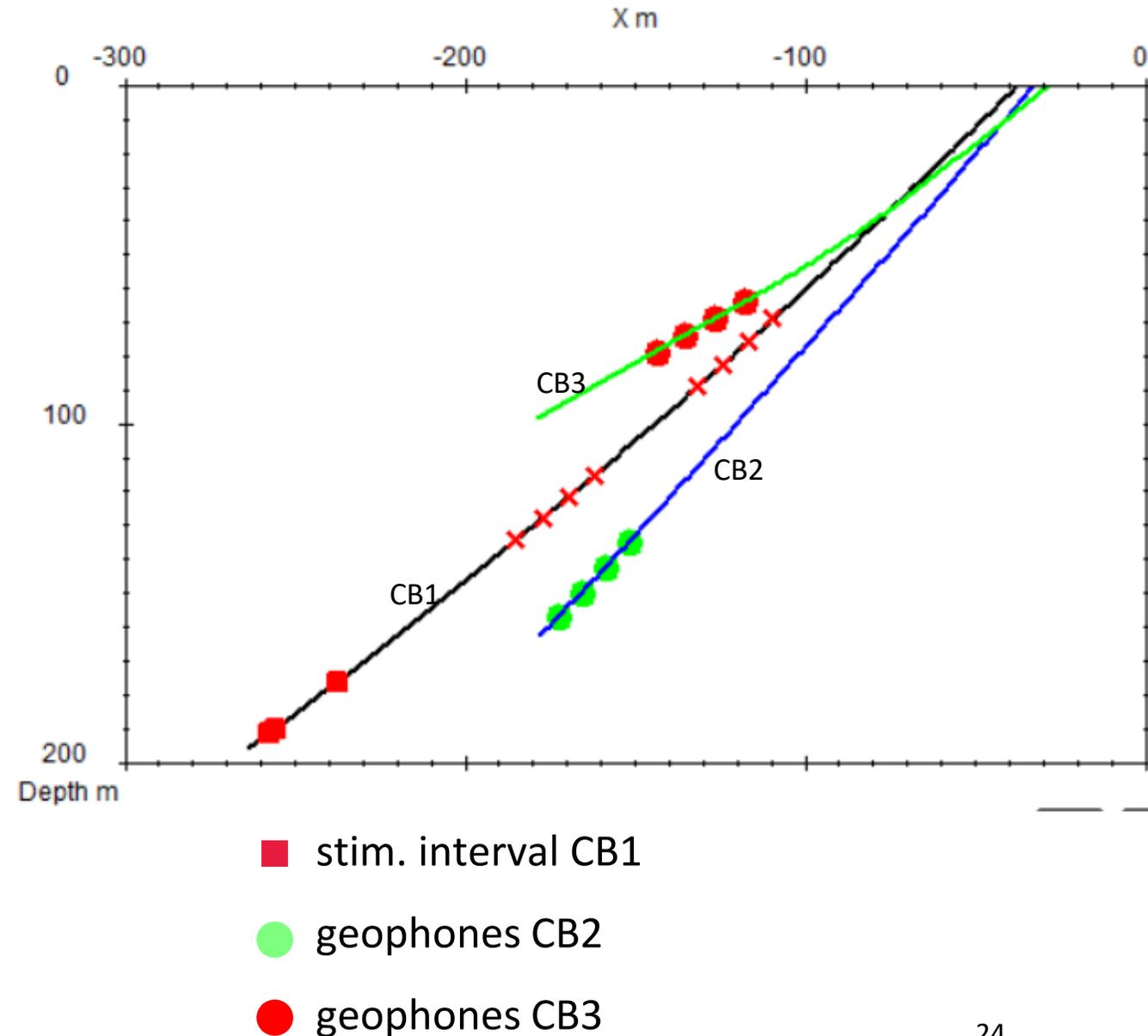
Seismic Risk TLS & ATLS

Seismic risk

- A seismic risk study was conducted beforehand, with recommendations for injection volumes and traffic light thresholds.

Induced seismic hazard, BULG

ETH zürich

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VON GRUND AUF DURCHDACHT

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ein Unternehmen von

Induced seismic hazard and risk analysis of hydraulic stimulation experiments at the Bedretto Underground Laboratory for Geoenergies (BULG)

Report

First Version: December 2018

Updated: April 2019

ETH Zürich

Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE)

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Seismic risk – traffic light

ZoDrEx

Derivation of proposed traffic light for stimulation test - with lower thresholds due to unknown rock parameters (high uncertainty in attenuation and magnitude)

- Taking proposed traffic light from risk study:

Green	Orange	Red
PPV < 5 mm/s M_w < 0.5 P(PPV>30 mm/s) < 0.01	PPV ≥ 5 mm/s M_w ≥ 0.5 P(PPV>30 mm/s) ≥ 0.01	PPV ≥ 30 mm/s M_w ≥ 1.2 P(PPV>30 mm/s) ≥ 0.1
No action	**Reanalysis of seismic hazard** If P(PPV>30 mm/s at 100 m) = a) < 0.01 proceed with caution at this interval b) 0.01- 0.1 abandon interval c) ≥0.1 turn to red	**Reanalysis of seismic hazard** Reconsider feasibility of experimental work at BULG

- Added extra safety factor ΔM~1.5 due to high uncertainties

- Proposed traffic light for stim test:

Green	Orange	Red
Mw<- 1 r_stim< 20m ppv<0.16mm/s	Mw>-1 r_stim >20m ppv>=0.16mm/s	Mw>0 r_stim >25m ppv>=1mm/s
No action	proceed with caution reduce injection rate 2 seismologists & 1 hydrologist at site consult ATLS prediction begin waiting period	**controlled bleed off (see bleed off concept)** convene a meeting

(Mw -1 ~ factor 100 below human perception @100m distance)

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Reaction & communication plan

- Red traffic light
  - Bleed off
  - Communicate and get advice from ETH expert team whenever a red event is detected.
  - Approval for continuation from ETH.

- Felt earthquake in tunnel
  - Bleed off
  - Assemble at lab entrance & leave tunnel
  - Inform Lab management team
  - Suspend operation
  - Watch SED tunnel seismometer data
 - Do not re-enter before O.K. of Lab management team

Seismic risk – Adaptive Traffic Light

- An ATLS prototype was run during the stimulation to be able to forecast seismicity in case of high seismicity rates and to test various forecasting algorithms

- The TLS was set up as a binding action scheme, the ATLS was planned for decision support

- In the end too few events were recorded to fully make use of the ATLS prediction capabilities
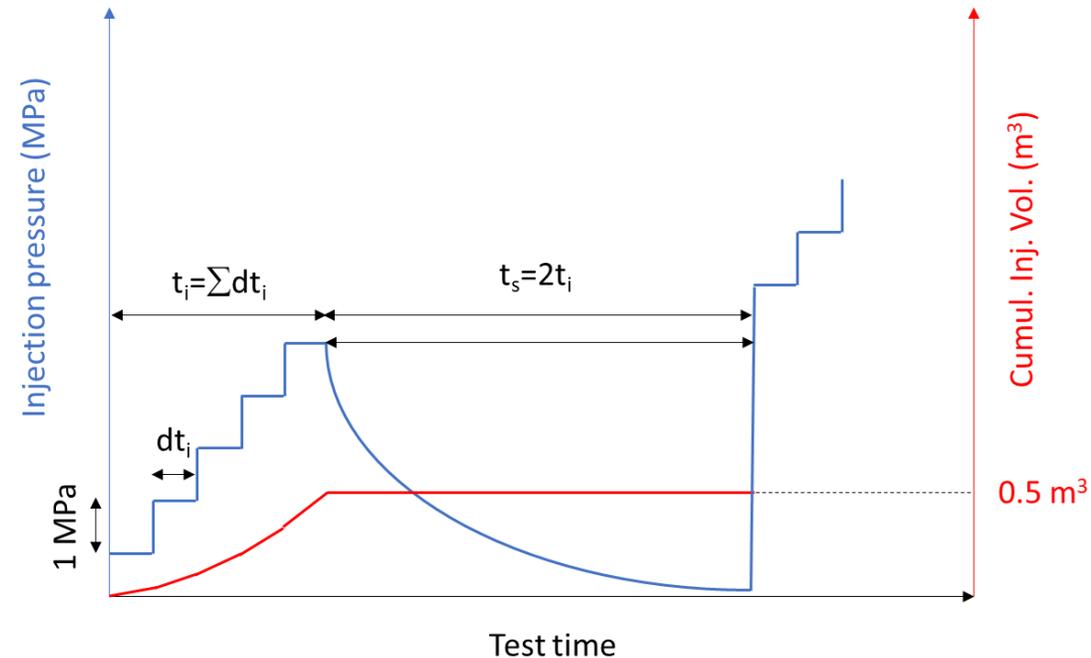
Stimulation scheme

Stimulation scheme (I/III)

- Sequence of controlled injection pressure and shut-in steps, followed by a bleed-off.

- Injection steps:
  - Pressure increases gradually after constant injection intervals
  - Injection step ends if (1) TLS turns red, or (2) the pressure downhole exceeds 0.75*FBP (breakout pressure), or (3) the injected volume during current step is 0.5 m^3

- Intermediate shut-in steps to mitigate seismic risk

- A bleed-off is carried out if (1) the TLS turns red or, (2) the pressure downhole exceeds 0.75*FBP or (3) the total injected volume is 5 m^3 per interval.

- Design parameters:
  - Amount of pressure increase.
  - Duration of the injection intervals dt_i
 - Duration of the shut-in steps
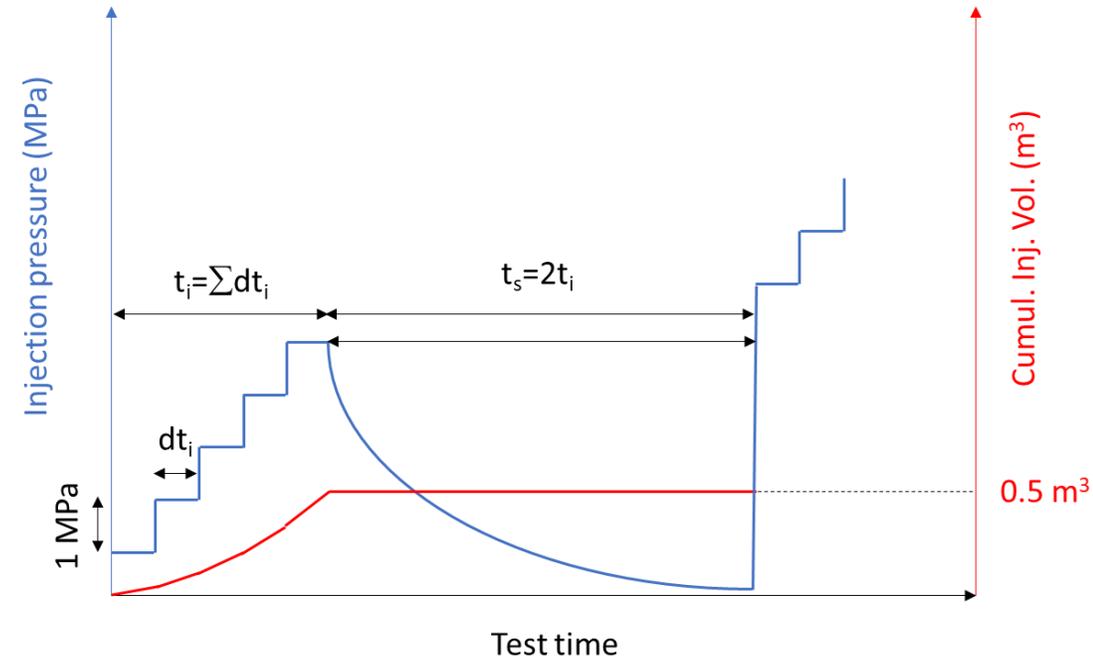
Stimulation scheme (II/III)

● Restrictions/targets:
  ○ A minimum overpressure of 5 Mpa at r=25m is required for 25% chances of shearing
  ○ The maximum flow rate (yield of the pump) is 40 L/min

● Methodology: 1D radial pressure model. T, S and r_{stim} do not vary with time

● Suggested design parameters:
  ○ Final design and test outputs largely depend on the initial transmissivity
  ○ Pressure increase=0.5-1 MPa (as in Grimsel).
  ○ Duration of the injection intervals dt_i=0.5-1h
  ○ Duration of the shut-in steps= twice the duration of the previous injection step.
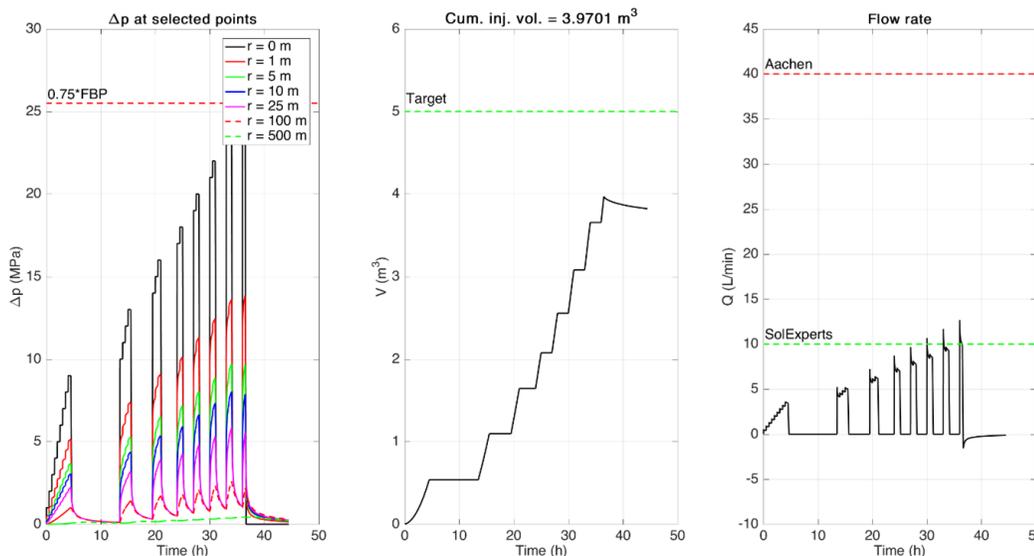 ○ Total expected duration= max. 24 hours.

Initial low T=1e-8 m^2/s
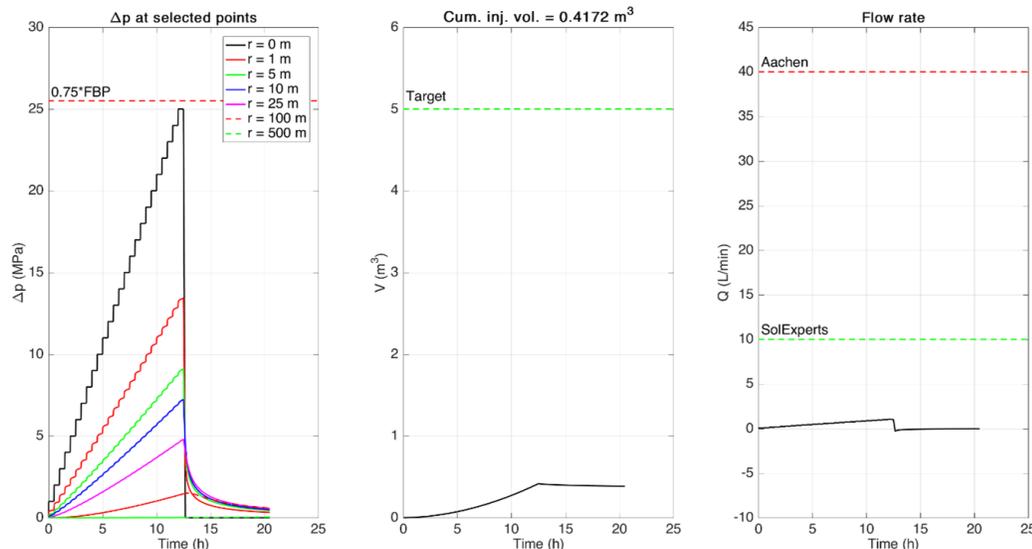
Initial high T=1e-7 m^2/s

- Two extreme cases involving very low/high fracture transmissivity have been evaluated.

- Goals:
  - Evaluate if overpressure at r=25m (magenta lines in left panels) are enough to cause shearing
  - Evaluate if the available pump (Q=10 L/min) is capable of providing sufficient downhole pressure (right panels).

- As observed, the pressure at r=25m is ca. 5 MPa regardless of initial transmissivity. This low pressure is unlikely causing shearing at that distance (see slide xxx in this document).
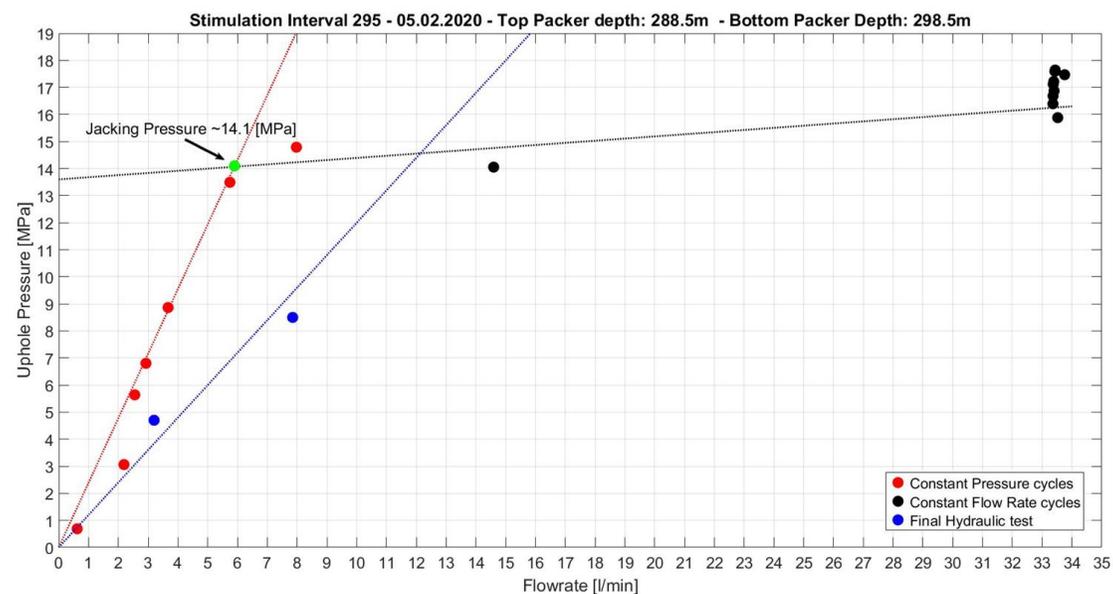
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Stimulation prognosis

Prognosis

Prediction of injection pressures needed to shear the structures present in each interval.

Interval designation	Interval length (m)	Top	Bottom	Orientation of dominant structure		Shearing pressure (MPa)		
				strike	dip	P25	P50	P75
STIM-250	2.7	249.0	251.7	227	38	12.7	14.2	15.6
STIM-267	2.7	265.7	268.4	218	88	10.2	12.1	13.8
STIM-269	9.9	264.0	273.9					
STIM-292	2.7	290.7	293.4	346	31	15.9	17.3	18.6
STIM-295	9.9	288.5	298.4					
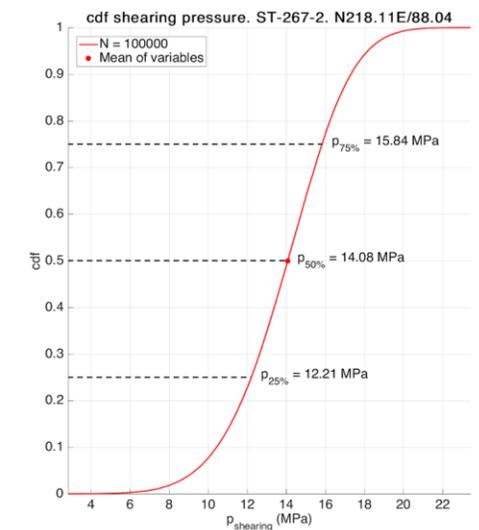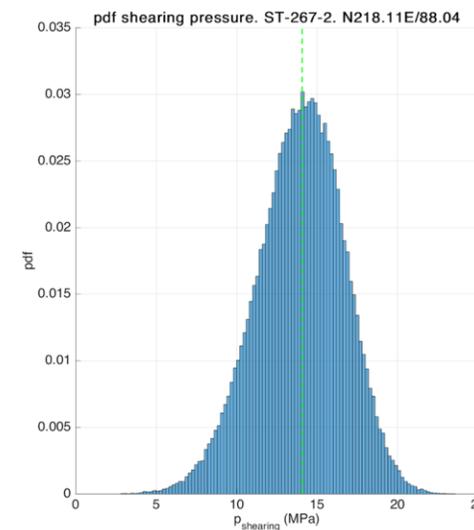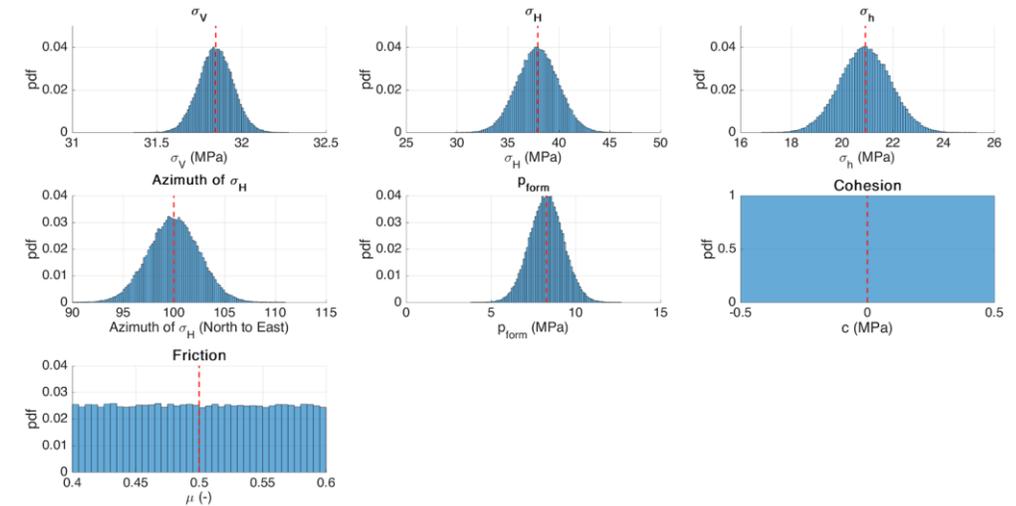
Results

Hydraulic data - Interpretation (I/II)
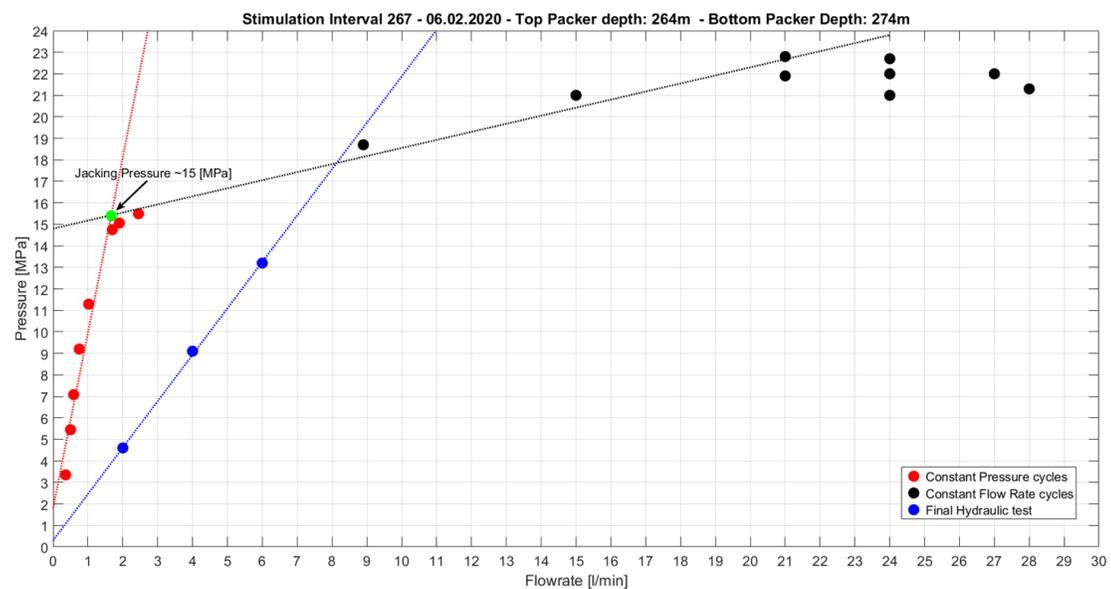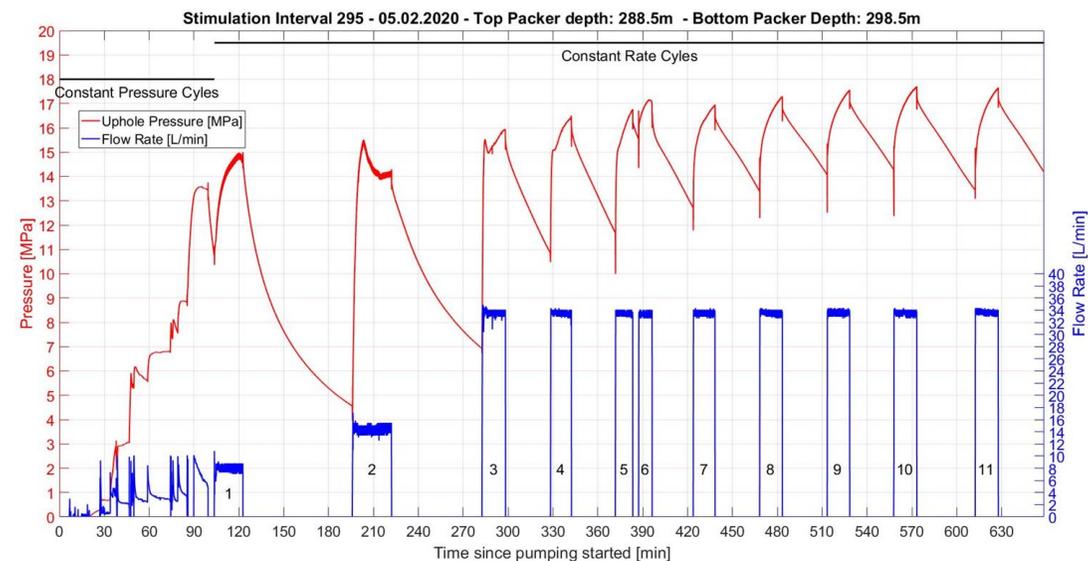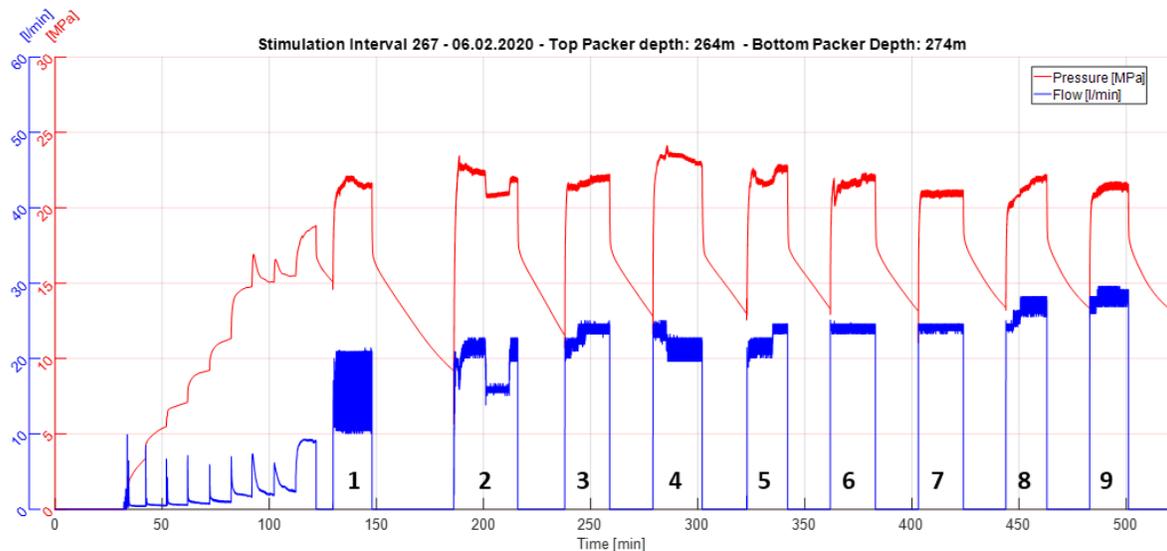
Hydraulic data - Interpretation (II/II)

Left Table

Borehole	CB1	Interval Depth	264 m to 274 m
Test Interval	STIM-267	Target Fracture	267 m
Test Type	Double Packer	Testing Date	06.02.2020
Authors		Report Date	13.02.2020

Test Interval Specifications:

Interval Length	10 [m]	Wellbore Radius	0.05 [m]
Jacking Pressure	15.41 [MPa]	Mean ISIP	17.55 [MPa]
Hydrostatic P	1.71 [Mpa]		

Test Description: A double-packer test system was installed at a depth of 264 m.
A stimulation was conducted (see activity report). It was done in 4 sections: Constant Pressure (0 to 121m), Constant Rate (121 to 536 min), Bleed-Off (536 to 1261 min) and Final Hydraulic Test (1261 to 1317 min).

Test Results:

Flow Model		Horner (1)	Nsights (2)	Cooper / Theiss (3)	Steady State (4)	Bisroy / C head (5)		ISIP	
Pulse test 29.10.2019		T			5.10E-10		[m2/s]		
Constant Pressure		T	8.30E-10				[m2/s]		
		S	4.30E-03				[-]		
Constant Rate	Cycle 1	T	2.40E-08				[m2/s]	16.93	[MPa]
	Cycle 2	T	3.78E-08				[m2/s]	17.35	[MPa]
	Cycle 3	T	4.71E-08				[m2/s]	1736	[MPa]
	Cycle 4	T	5.00E-08				[m2/s]	17.05	[MPa]
	Cycle 5	T	4.89E-08				[m2/s]	17.32	[MPa]
	Cycle 6	T	5.22E-08				[m2/s]	17.59	[MPa]
	Cycle 7	T	5.50E-08				[m2/s]	18.03	[MPa]
	Cycle 8	T	6.20E-08				[m2/s]	17.98	[MPa]
	Cycle 9	T	5.10E-08				[m2/s]	18.10	[MPa]
Bleed-Off		T			1.23E-08				
Hydraulic test	Step-Rate	T	3.56E-08	3.04E-08		2.93E-08	[m2/s]		
	Injection	S	7.26E-05	2.49E-04		2.40E-04	[-]		
	Shut-In	T	2.37E-08		1.04E-08		[m2/s]		
							[-]		
	Constant	T				7.80E-08	[m2/s]		
	Head	S				1.20E-05	[-]		

(1) Horner time T estimation using Theis recovery method
(2) Nsights simulator with n=2.
(3) Jacob-Cooper or Theiss solution
(4) Thiem Steady-State solution.
(5) Bisroy Deconvolution for Step-Rate or Jacob and Lohman solution for Constant Head

Right Table

Borehole	CB1	Interval Depth	288.5 m to 298.5 m
Test Interval	STIM-295	Target Fracture	292 m
Test Type	Double Packer	Testing Date	05.02.2020
Authors		Report Date	13.02.2020

Test Interval Specifications:

Interval Length	10 [m]	Wellbore Radius	0.05 [m]
Jacking Pressure	14.09 [MPa]	Mean ISIP	16.08 [MPa]
Hydrostatic P	1.9 [Mpa]		

Test Description: A double-packer test system was installed at a depth of 288.5 m.
A stimulation was conducted (see activity report). It was done in 4 sections: Constant Pressure (0 to 100m), Constant Rate (100 to 650 min), Bleed-Off (650 to 1300 min) and Final Hydraulic Test (1300 to 1350 min).

Test Results:

Flow Model		Horner (1)	Nsights (2)	J. Cooper (3)	Steady State (4)		ISIP	
Constant Pressure		T	9.60E-09			[m2/s]		
		S	1.00E-02			[-]		
Constant Rate	Cycle 1	T	1.73E-08			[m2/s]	14.54	[MPa]
	Cycle 2	T	2.28E-08			[m2/s]	13.64	[MPa]
	Cycle 3	T	2.93E-08			[m2/s]	15.26	[MPa]
	Cycle 4	T	2.98E-08			[m2/s]	15.94	[MPa]
	Cycle 5	T	3.21E-07			[m2/s]	16.29	[MPa]
	Cycle 6	T	3.62E-08			[m2/s]	16.47	[MPa]
	Cycle 7	T	3.98E-08			[m2/s]	16.51	[MPa]
	Cycle 8	T	4.65E-08			[m2/s]	16.85	[MPa]
	Cycle 9	T	4.70E-08			[m2/s]	17.05	[MPa]
	Cycle 10	T	3.23E-08			[m2/s]	17.2	[MPa]
	Cycle 11	T	4.18E-08			[m2/s]	17.17	[MPa]
Bleed-Off		T			2.07E-08	[m2/s]		
Hydraulic test	Recovery	T	5.82E-08			[m2/s]		
	Injection	T		7.35E-08		[m2/s]		
		S		2.00E-04		[-]		

(1) Horner time assuming 4 days of continuous drawdown for BU-1. T estimation using Theis recovery method
(2) Nsights simulator with n=2.
(3) Jacob-Cooper solution
(4) Thiem Steady-State solution.

Microseismicity

- 44 events were captured by automatic event detector

- 27 events could be auto-located

- Magnitude range from M=-3 to M=-2.6

- Post processing planned in the following week(s)
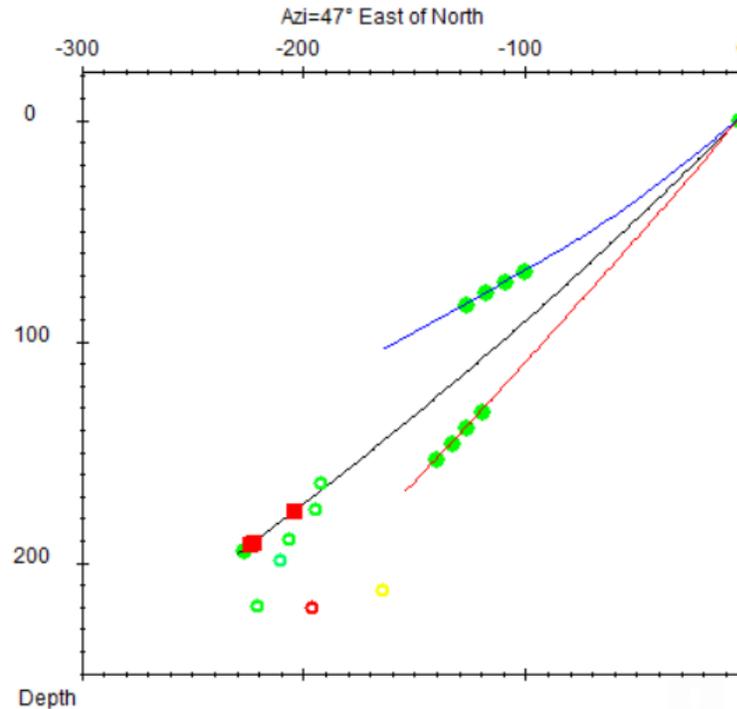
Seismicity during stimulation of bottom interval (STIM-295)
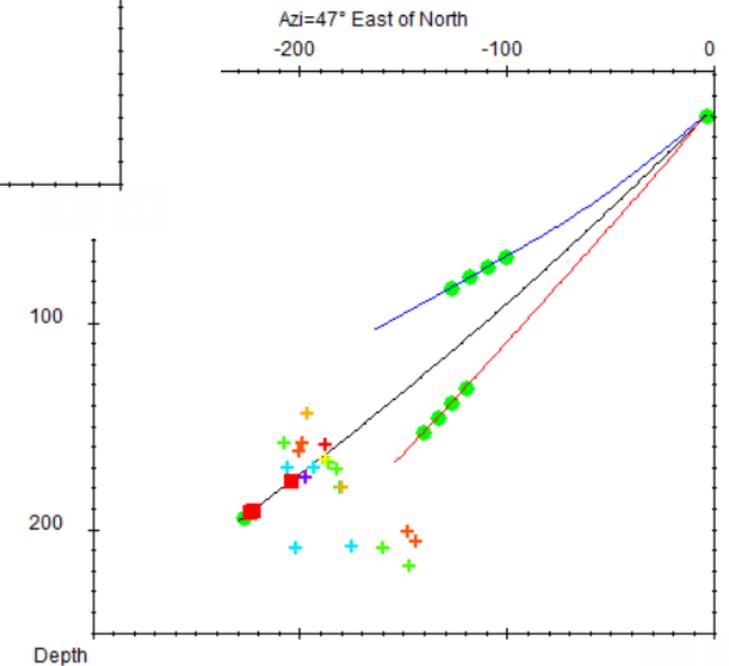
Seismicity during stimulation of top interval (STIM-269)

39

Image logs

- Most targeted intervals included exclusively natural fractures.

- Some intervals included axial fractures induced by minifracs tests (performed previous to the DESTRESS test).

- The presence of these axial fractures seems to have helped the stimulation of these otherwise tight intervals
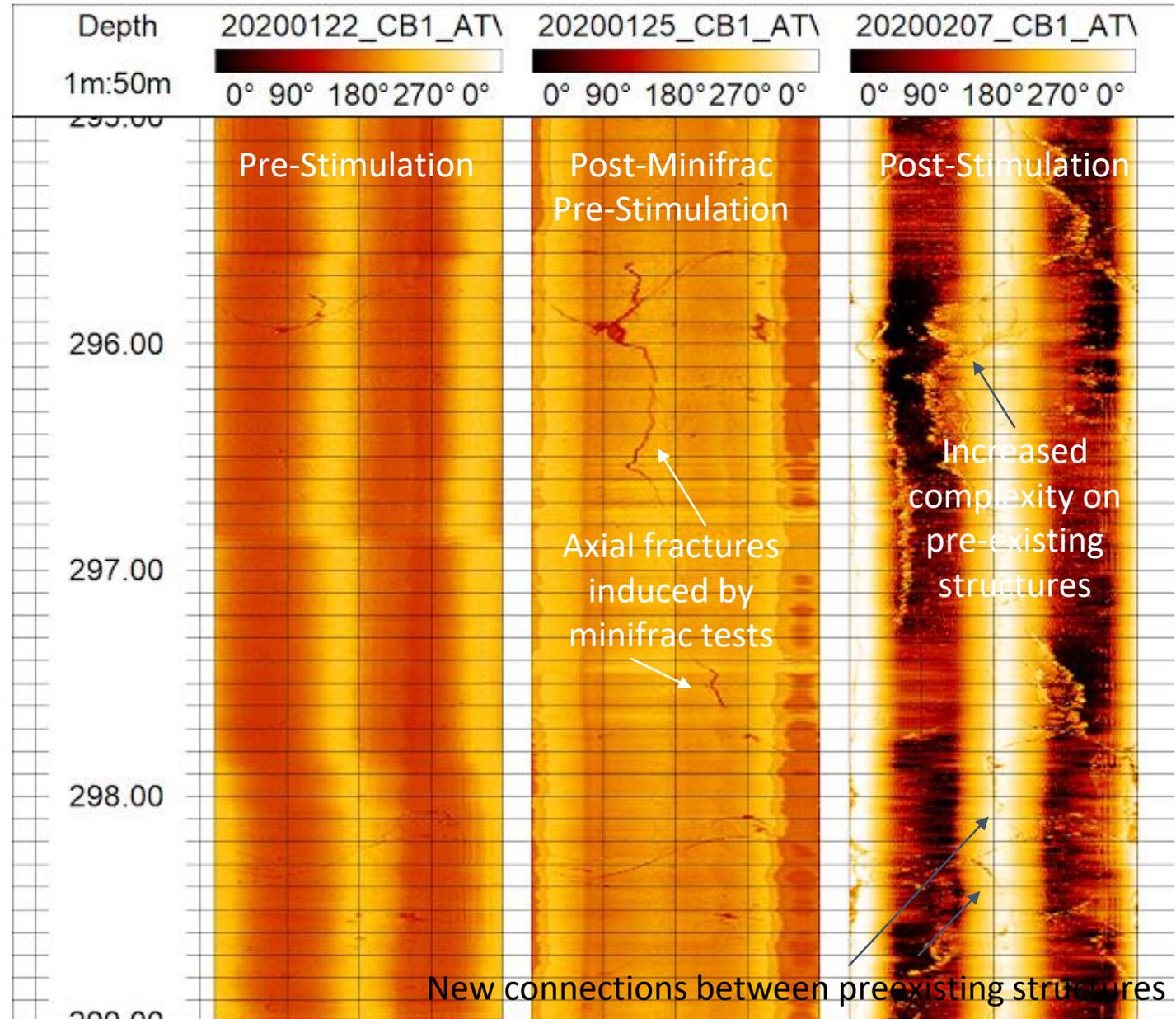
Borehole Ground Penetrating Radar
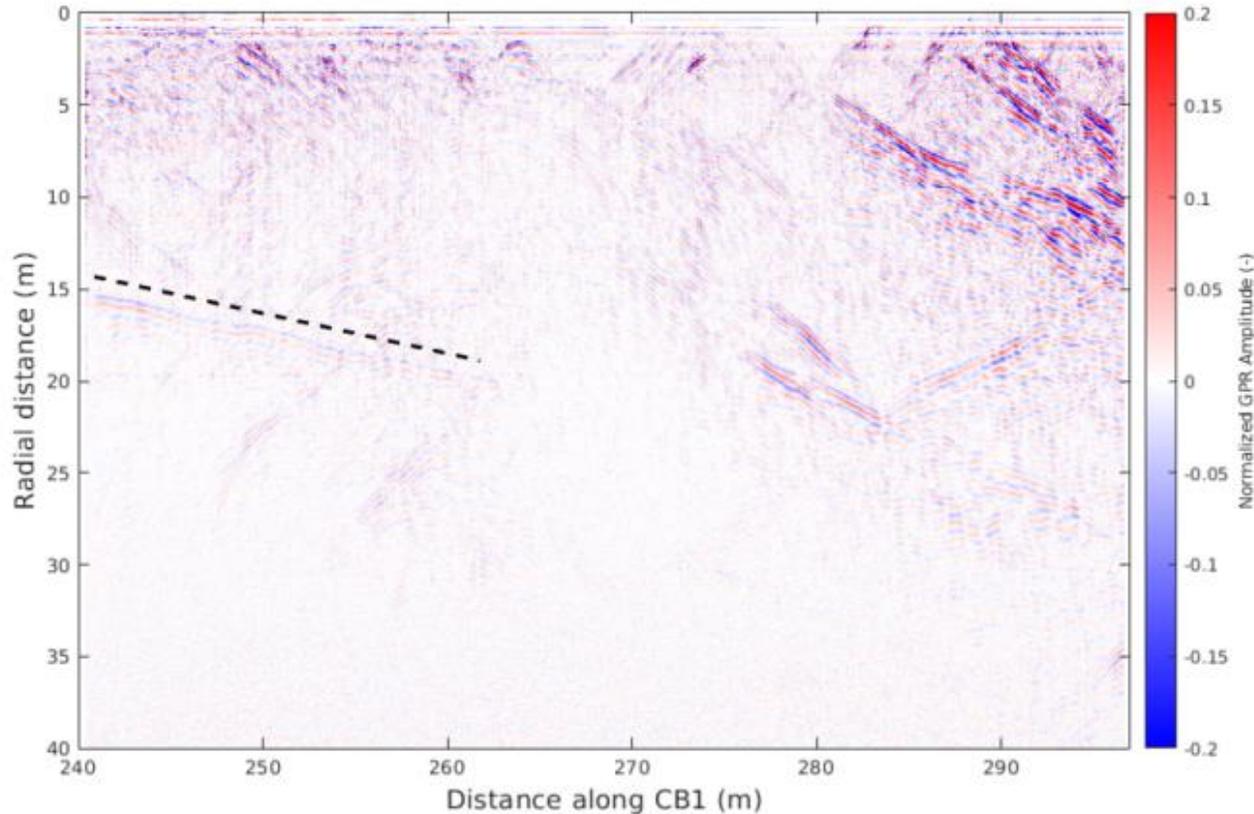
Difference for the 100 MHz GPR measurement induced by the stimulation experiments (ETH, unpublished).

- Comparison of ground penetrating radar data before and after stimulation shows increased contrast in the lower (stimulated) part of well CB1.

- The main changes in reflectivity (hence aperture and water content of fractures) is seen in the lower interval of CB1, where GES successfully stimulated

Achievements

- The stimulation operations carried out in the Bedretto lab managed to successfully increase the transmissivity around the stimulated borehole by factors ranging from x7 to x60.

- Induced seismicity was detected. Magnitudes range between -3 and -2.6.

- Microseismicity was located around the well in the proximity of stimulated intervals

Seismicity during stimulation of interval STIM-269
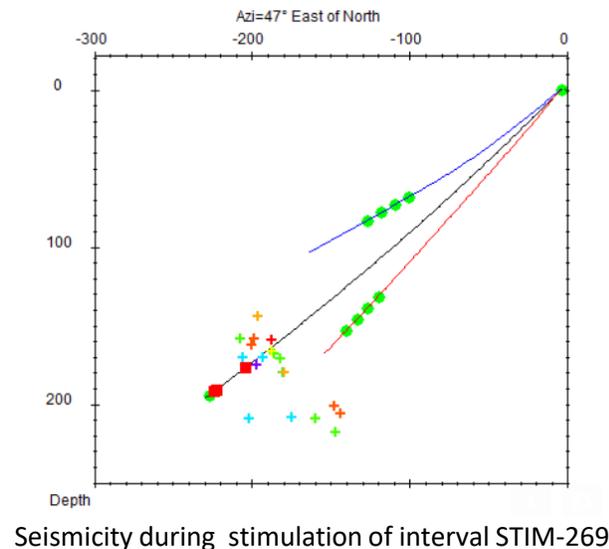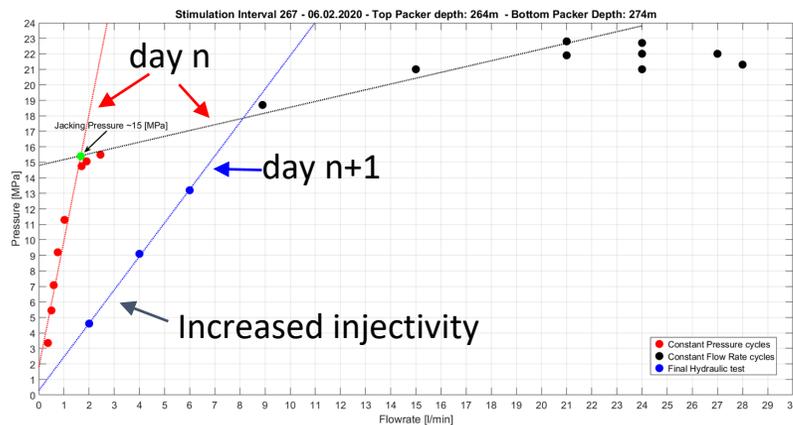
BH GPR data shows increased amplitudes (increased aperture and water content) after the test stimulation
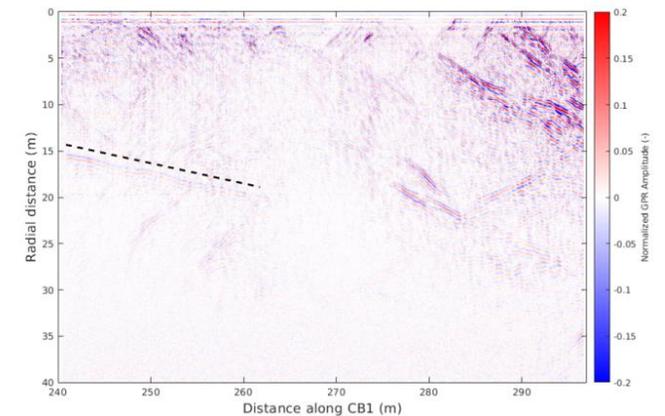
Lessons Learned

- Stimulation of pre-existing structures in granitic rocks is possible with the consequent increase in transmissibility while keeping the induced seismicity to a minimum.

- Stimulation of tight structures (i.e. closed and healed fractures) proved to be very difficult.

- A previous step of controlled hydraulic fracturing might be necessary to run a successful shear stimulation afterwards in this kind of tight intervals (case of STIM-295).

- Previously open structures (STIM-267) can be successfully stimulated without previous hydraulic fracturing.