In situ gas fracturing experiments conducted in the Callovo-Oxfordian claystone

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PHD SCHOOL

EURAD Training course

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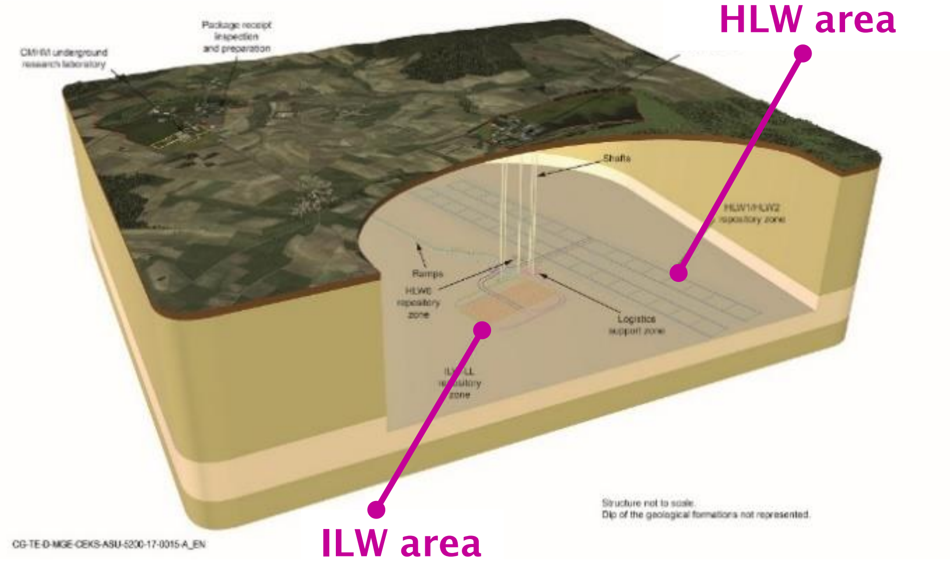
European Joint Programme on Radioactive Waste Management

Context

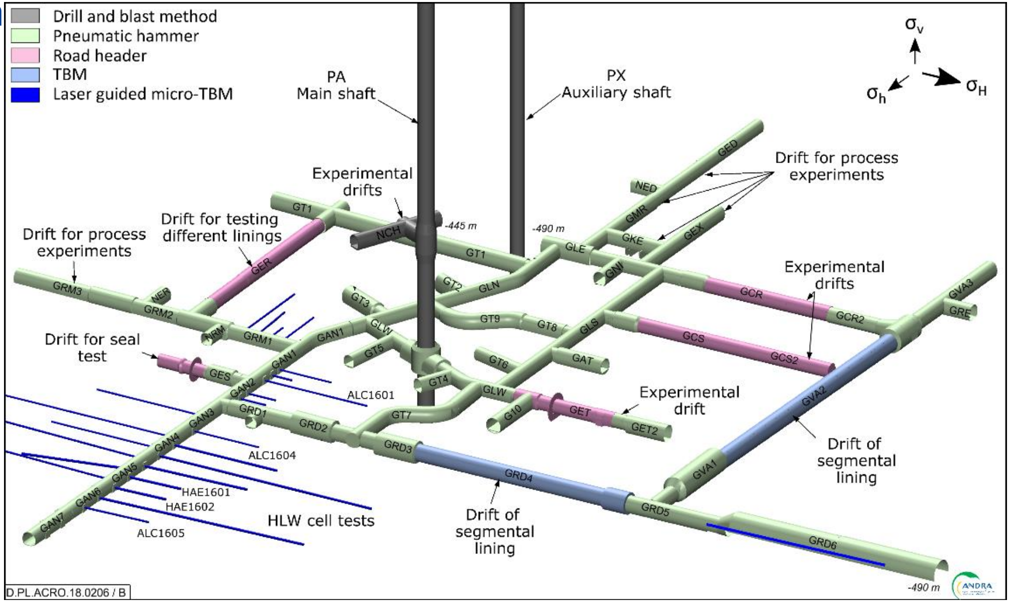
Context
The Cigéo project

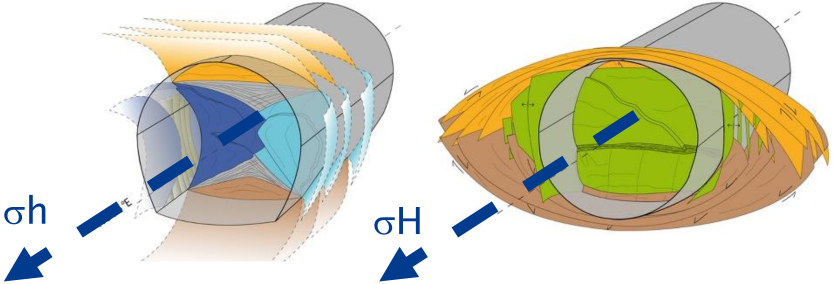
- **Andra** is in charge of the management and disposal of radioactive waste in France
- **Cigéo** is the French Industrial Center for **Geological Disposal** for **HLW** and **ILW**
  - Licence application in December 2022
  - Location in the eastern part of the Paris basin into a claystone formation
- **Callovo-Oxfordian (COx)**
  - Depth of 500 m
  - Favorable characteristics
    - very low hydraulic conductivity
    - low molecular diffusion
    - high retention capacity for radionuclides



Context
The Meuse/Haute-Marne URL

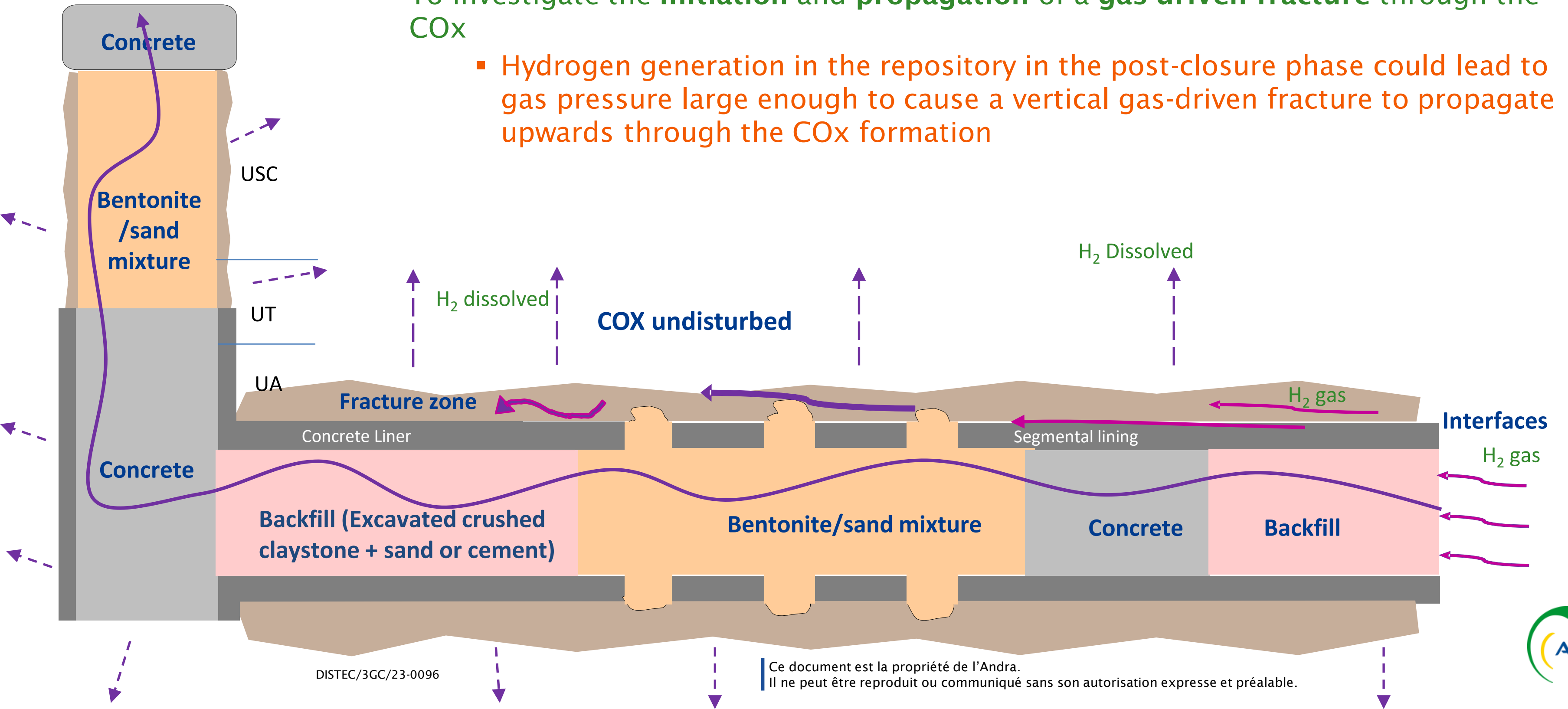
- Enables scientific and technological research to be carried out directly within the COx
- Objectives in geomechanics
  - To study **hydro mechanical** behavior
  - To characterize the **Thermo Hydro Mechanical** behavior
  - To perform **sealing experiments**
  - To characterize the **E**xcavation **D**amaged **Z**one
    - Shape depends on the excavation orientation wrt to σh or σH





Context
Gas migration in the repository

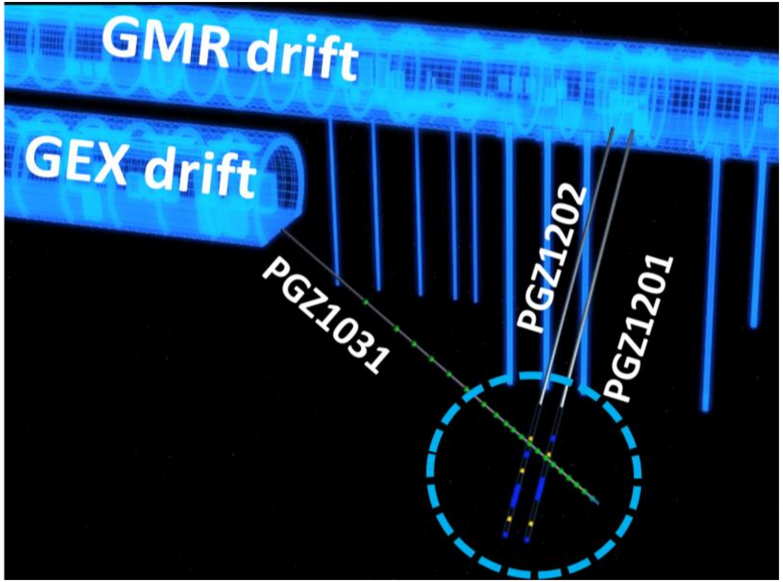
- To investigate the **initiation** and **propagation** of a **gas-driven fracture** through the COx
  - Hydrogen generation in the repository in the post-closure phase could lead to gas pressure large enough to cause a vertical gas-driven fracture to propagate upwards through the COx formation



PGZ1 experiment

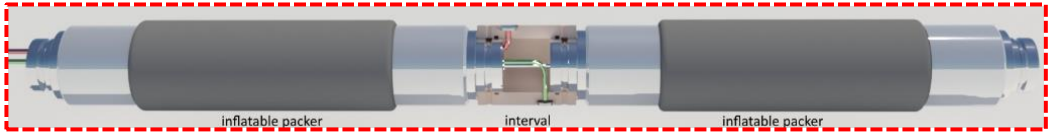
PGZ1
Objective

- PGZ1 is dedicated to identify **gas migration mechanisms** into the COx claystone at different pressure levels
  - Series of gas injection tests at different flow rates
  - Gas: Nitrogen
- 3 instrumented boreholes drilled and equipped in July 2009

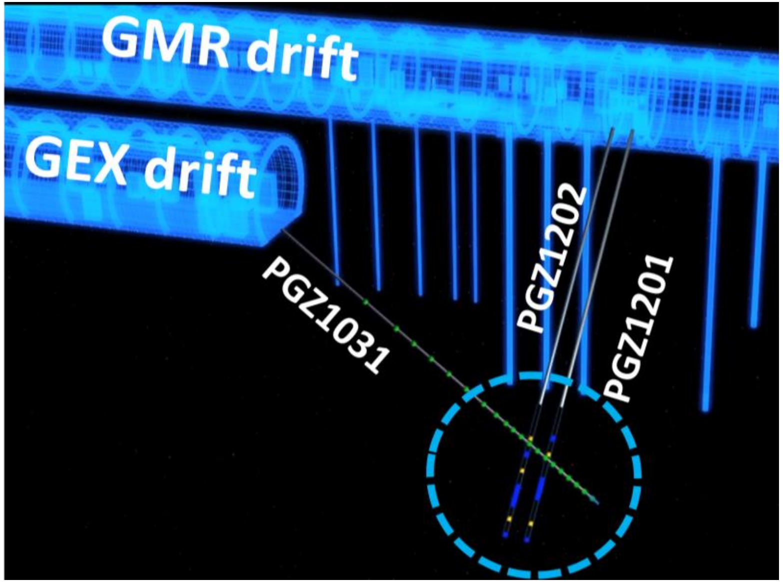


PGZ1
Borehole characteristics

- **PGZ1201** & **PGZ1202** drilled from the GMR drift
  - Length: 28 m, spacing: 0.9 m
  - Oriented parallel to σH
  - Equipped with a multipacker system to monitor water/gas pressure in 3 intervals: PGZ120x_01, 02 & 03

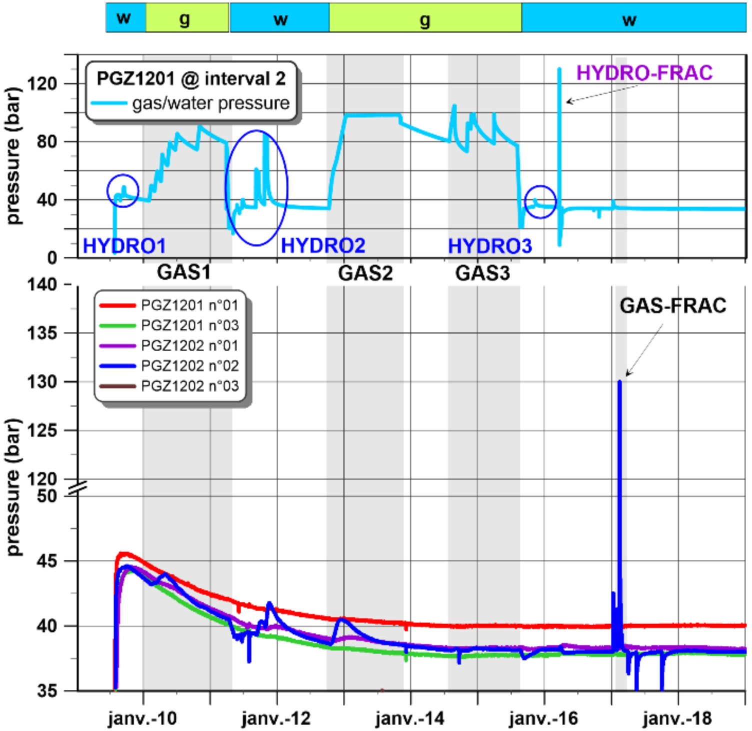


- **PGZ1031** drilled from the GEX drift
  - Equipped with a multiple magnetic extensometers probe (MagX system®) to monitor axial deformation



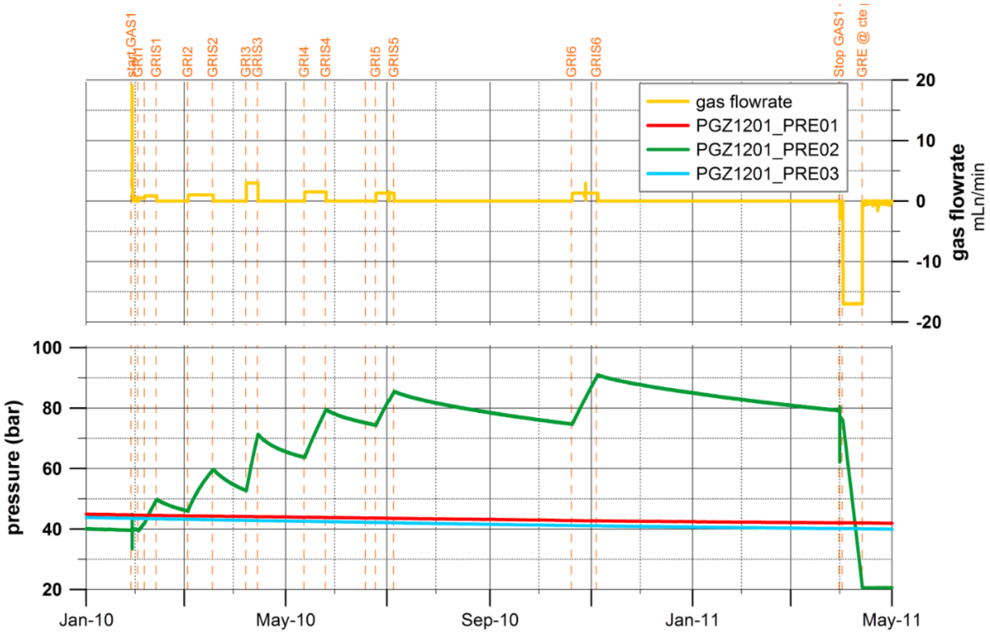
PGZ1
Overview

- 10 years of water/gas pressure monitoring
  - Pore pressure in intervals
  - Mechanical pressure in packers
- PGZ1201_02
  - **HYDROx**: Water permeability tests
  - **GASx**: gas injection tests at low rate (slow test)
  - **HYDO-FRAC**: water injection test to measure σh
- PGZ1202_02
  - **GAS-FRAC**: gas injection test at high flow rate (fast test)



PGZ1
PGZ1201 - GAS1 (slow test)

- 6 constant gas flow steps (GRIx) followed by pressure recovery periods (GRISx):
  - maximal pressure = 9.1 MPa
- Classical two-phase flow model reproduces reasonably well observations
  - Two separate zones with different gas entry pressure are required:
    - Inner zone corresponds to the Borehole Damage Zone with a very low gas entry pressure (≤ 2 MPa)
    - Outer zone corresponds to the sound claystone with a high gas entry pressure



ANDRA

PGZ1

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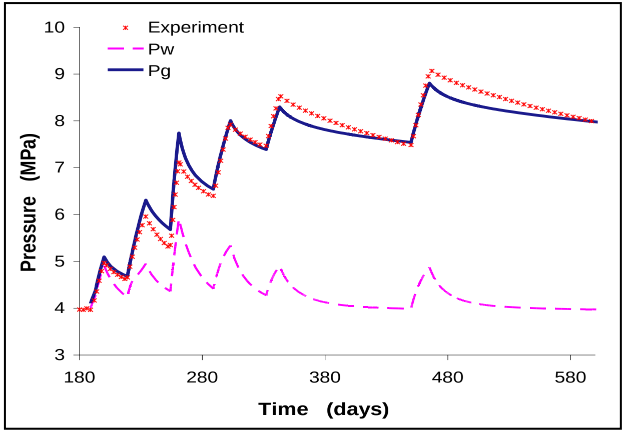
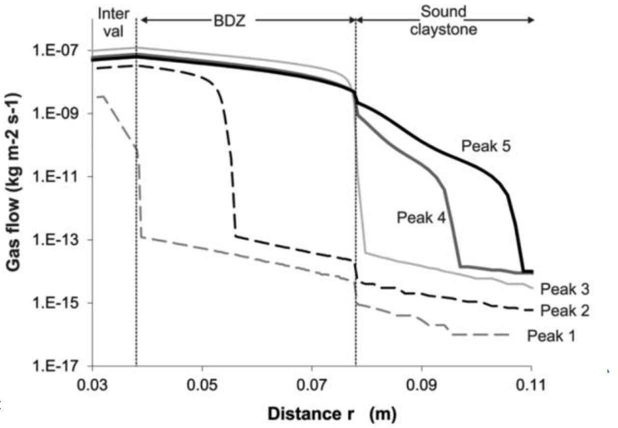
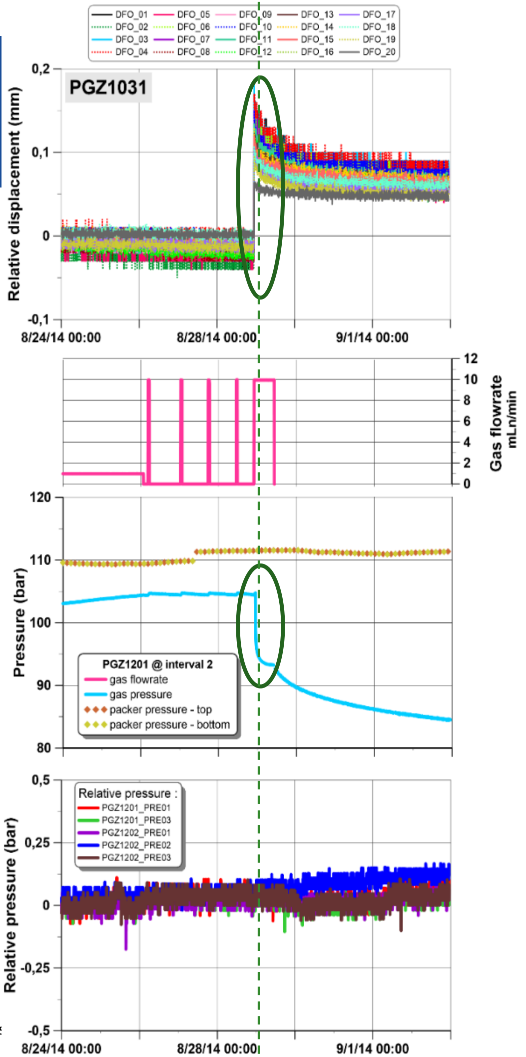




PGZ1
PGZ1201 – GAS3 (slow test)

- Constant injection flow rate test until reaching 10.45 MPa
- Then injection was turned to constant injection pressure
  - A sudden gas breakthrough was observed at 10.45 MPa
    - the gas pressure suddenly dropped in the test interval and the flow meter has reached simultaneously its maximum value
- A gas fracture was created with a gas pressure value well **below** the minimum principal stress component (σh ~ 12.5 MPa)
  - an overall rigid motion is detected on the extensometer string in borehole PGZ1031

It was not possible to locate the position of the fracture

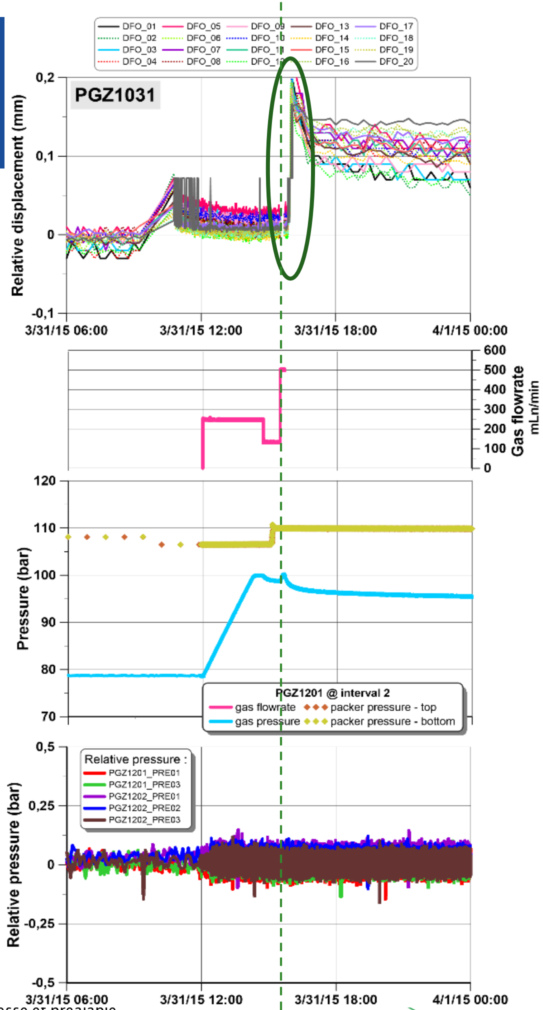


PGZ1

PGZ1201 – GAS3 (slow test)

- A new gas injection step was performed a few months later with a gas mixture (nitrogen + helium) and high gas flow rate
  - Helium is used as a gas tracer
    - Detection of helium is done on PGZ1031 head
  - A maximal gas pressure is reached at 9.99 MPa
- During this test, no displacement was detected by the extensometer string
  - The recorded motion is due to human action

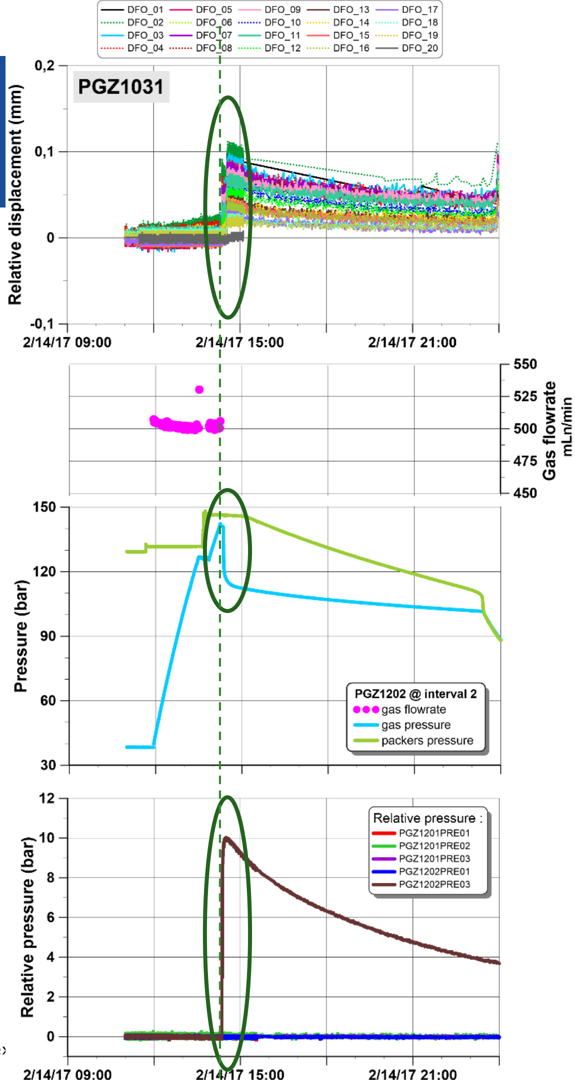
This is evidence that a fracture was created in the rock



PGZ1
PGZ1202 – GAS-FRAC (fast test)

- GAS-FRAC started with an injection at high constant flow rate @ 500 mLn/min that lasted about 2 hours
- The interval pressure reached progressively 14.18 MPa when the injection line was closed in order to monitor the pressure drop
  - Six minutes after the injection line was closed a sudden pressure drop was observed with:
    - a simultaneous increase in pressure in PGZ1202_03
    - a sudden differential displacements recorded by the PGZ1031
- A gas fracture was created with a gas pressure value well **above** the minimum principal stress component (σh ~ 12.5 MPa)

One packer starts to leak : the testing program has been abandoned



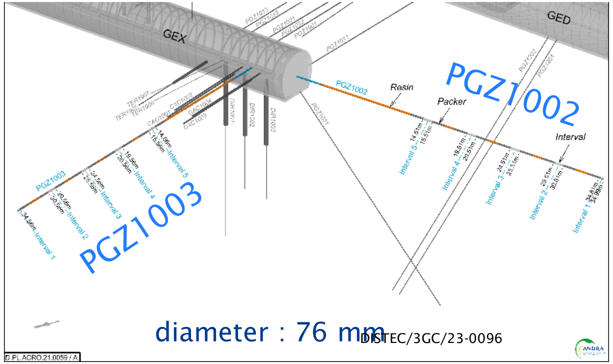
PGZ1
Summary

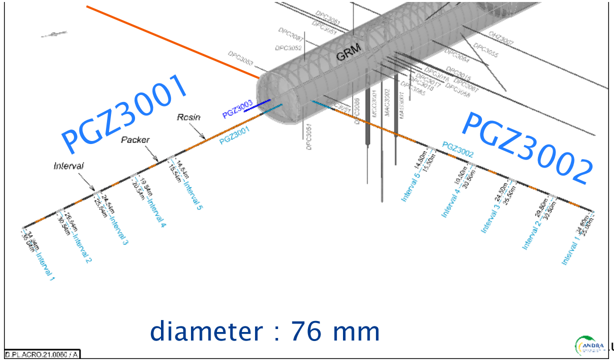
- Different gas injection tests at various flow rates (from 1 mLn/min to 500 mLn/min) have been conducted
- GAS1 reveals that generalized Darcy's law allows for the correct modelling of measurements up to 9.1 MPa
  - Gas first percolates radially into the BDZ and then starts to migrate into the sound claystone (with a high gas entry pressure above 4 MPa)
  - Analysis of the different gas injection phases reveals that generalized Darcy's law allows for the correct modelling of measurements up to 9.1 MPa
- During GAS3 & GAS-FRAC, a relationship between gas flow rate and gas fracturing pressure is highlighted
  - Some hypothesis
    - Drained/undrained boundary condition
    - Geometry of the cavity (shape and size of the BDZ)
    - The stress applied by the packers

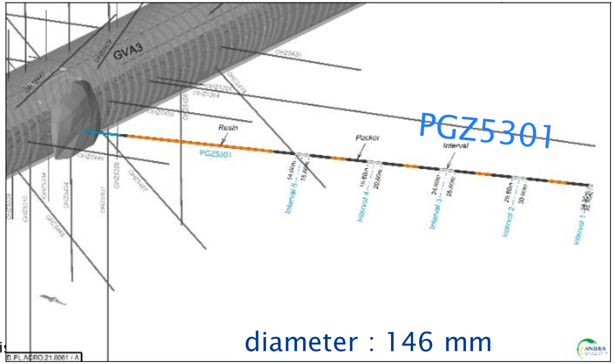
PGZ3 experiment

PGZ3
Objectives

- Study the gas fracturing pressure at different injection flow rates
- New boreholes have been drilled since 2020
  - Length 35 m
  - Oriented according to the horizontal principal stresses
    - **PGZ1002** & **PGZ1003** drilled from the GEX drift
    - **PGZ3001, PGZ3002** & **PGZ3004** drilled from the GRM drift
    - **PGZ5301** drilled from the GMA drift

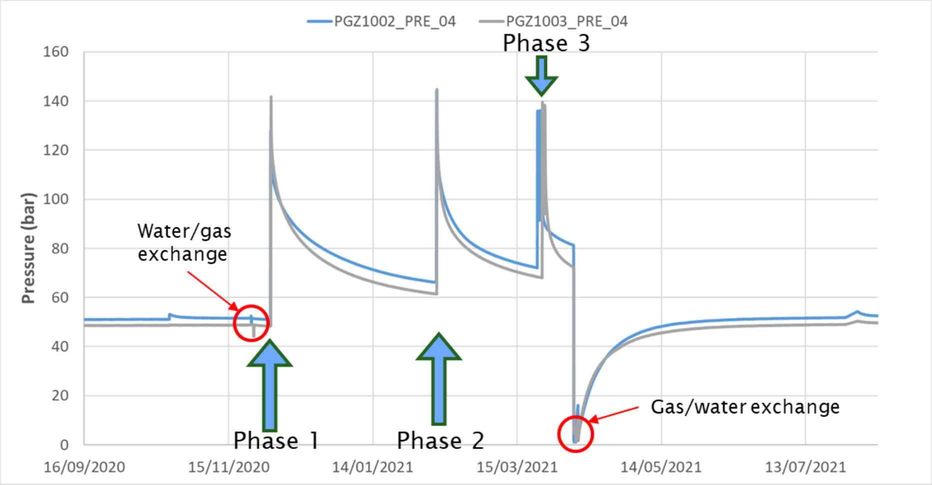






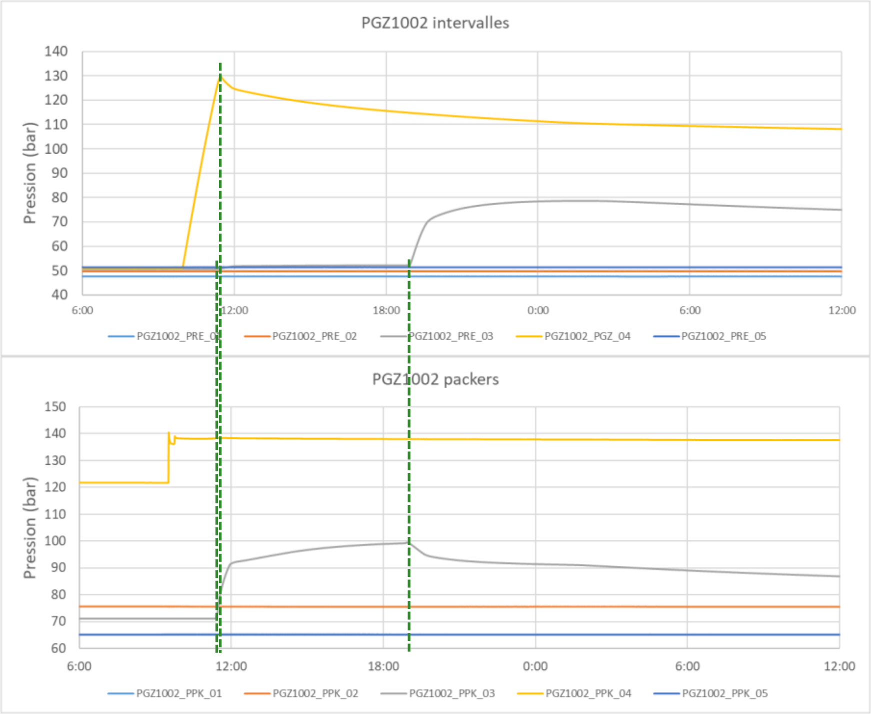
PGZ3
PGZ1002 & PGZ1003 - (fast tests)

- Injection inteval 4:
  - Located at 20 m from the drift wall
- 3 phases of gas injection tests (~ 500 mLn/min)
  - Phase 1 (December 2020):
    - to reach the breaking point of the rock
  - Phase 2 (February 2021):
    - To reopen the fracture
  - Phase 2 (March 2021):
    - to stimulate and reopen the fracture



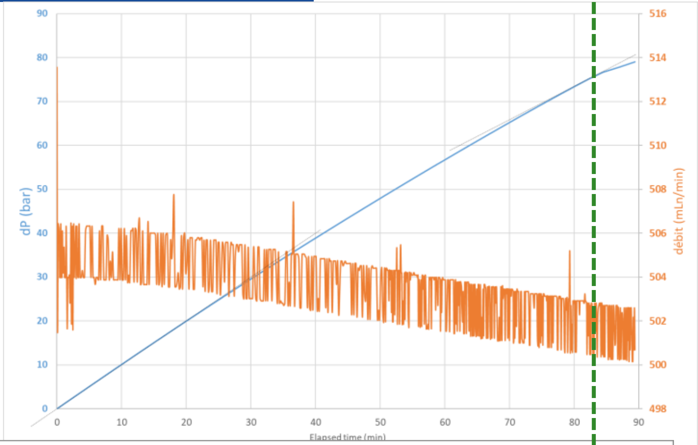
PGZ3
PGZ1002 - fast test (Phase 1)

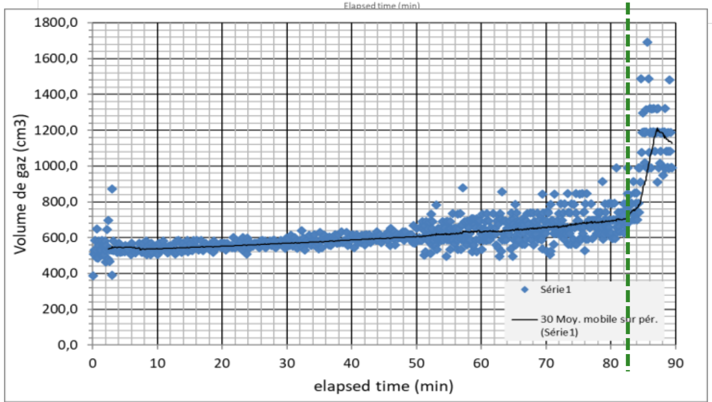
- Gas injection test : ~ 90 min
- Max. gas pressure : 13.01 MPa
- Interferences:
  - Packers @ interval 3
  - Interval 3 : much deeper (25 m)
    - Interface leakage ?
    - Possible creation of a opening along the borehole?



PGZ3
PGZ1002 - fast test (Phase 1)

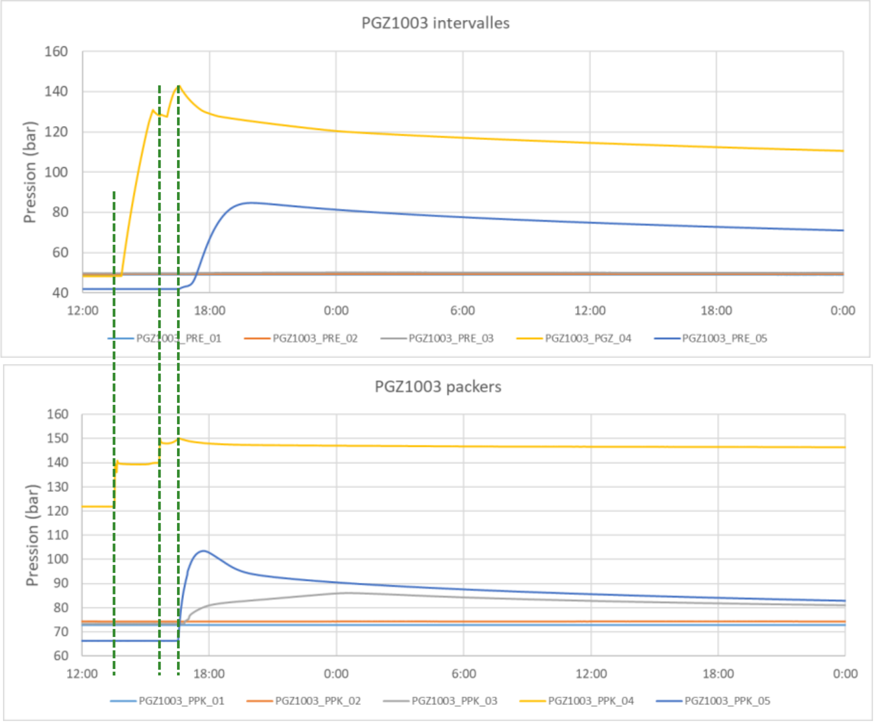
- Pressure build-up
  - Not perfectly linear
    - Gas volume variation
  - Inflection observed towards dP = 74.83 bar or 12.78 MPa in absolute pressure
    - correlated with the reaction of packers (interval n° 3)
- Gas volume variation
  - ideal gas law with gas deviation correction (Z factor: compressibility factor)
    - Volume of ~530 mL at the start of the injection (value greater than the volume of water extracted)
  - Slow increase in gas volume until inflection





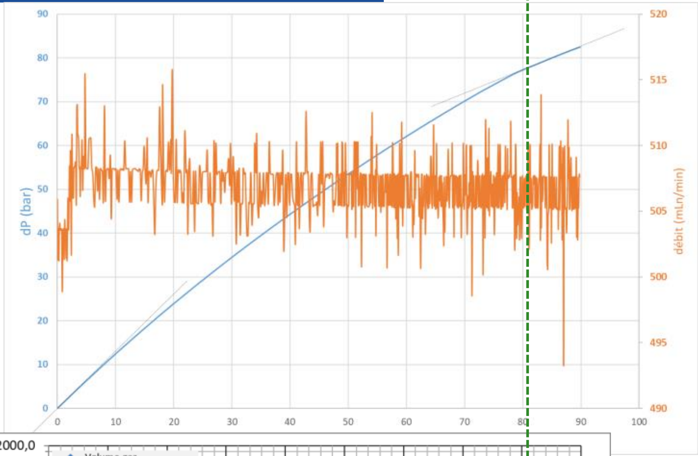
PGZ3
PGZ1003 - fast test (Phase 1)

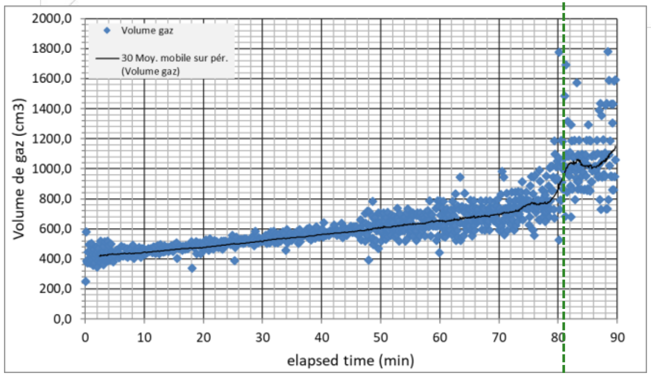
- First step : ~ 90 min
  - Gas pressure end ~ 13.01 MPa
- Second step: ~ 35 min
  - Max. gas pressure : 14.28 MPa
- Interferences:
  - Packers @ interval 3 + interval 5
  - Interval 5 : shallower (15 m)
    - Interface leakage ?
    - Possible creation of a opening along the borehole?



PGZ3
PGZ1003 - fast test (Phase 1)

- First step
  - Not perfectly linear pressure build-up
  - Gas volume variation
    - Volume of ~415 mL at the start of the injection (value greater than the volume of water extracted)
    - Slow increase in gas volume until inflection
  - Inflection observed towards dP = 79,87 bar i.e. 12,5 MPa in absolute pressure

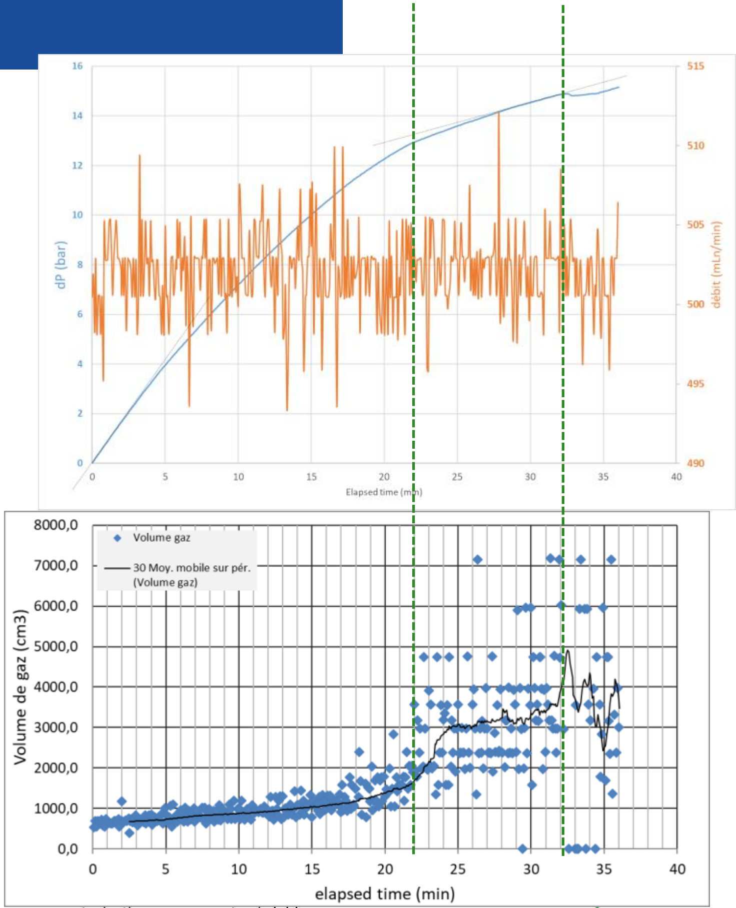




PGZ3

PGZ1003 - fast test (Phase 1)

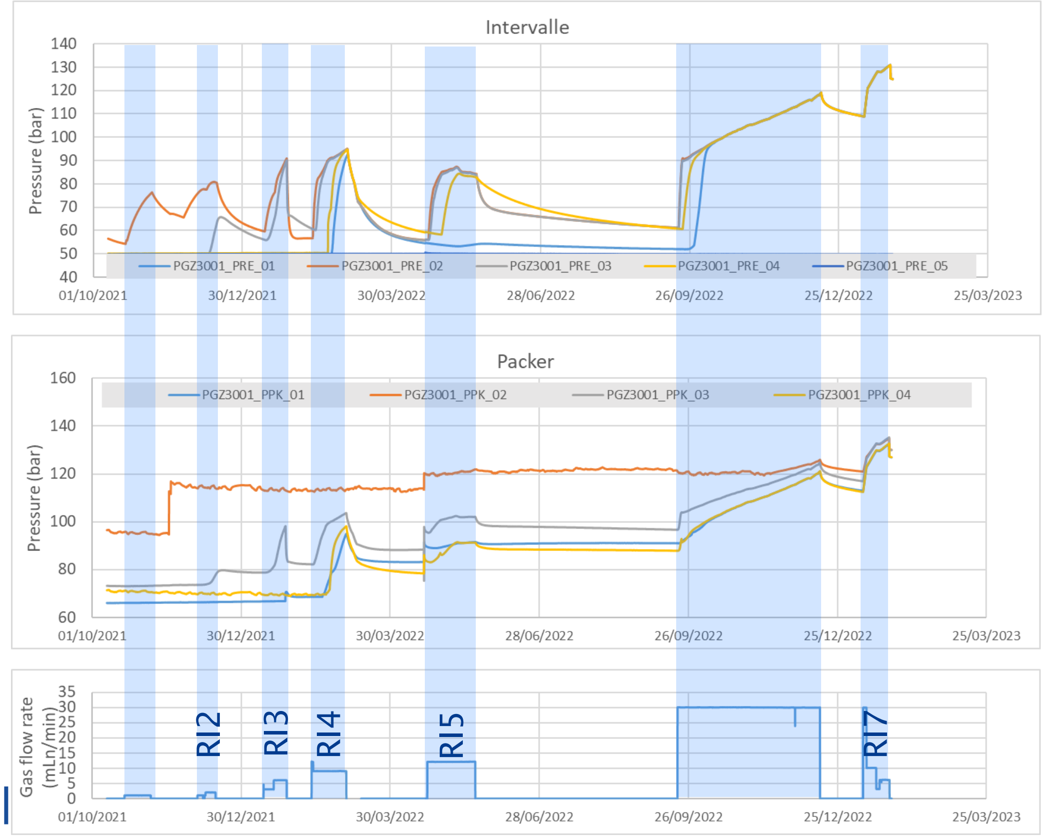
- Second step
  - Not perfectly linear pressure build-up
  - Gas volume variation
    - Volume of ~655 mL at the start of the injection (value lower than the volume at the end of the previous step)
    - Slow increase in gas volume until inflection
  - 2 inflection points observed at :
    - 14.05 MPa
    - 14.25 MPa
  - Max gas pressure : 14.28 MPa



PGZ3

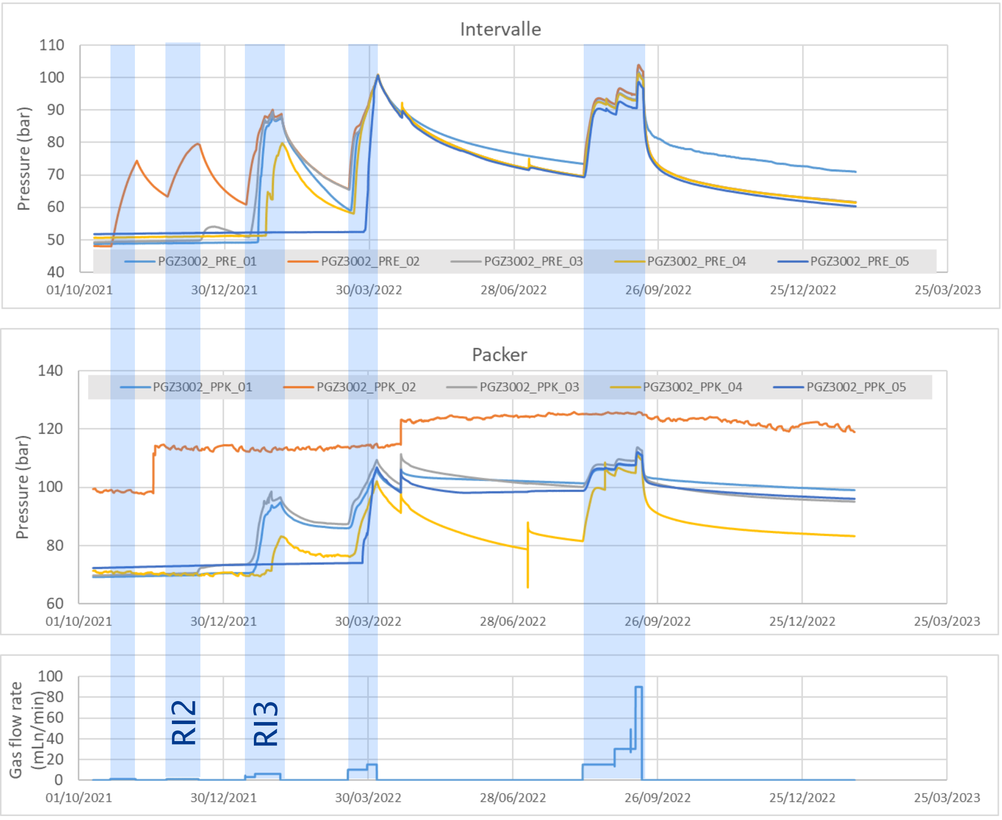
PGZ3001 - slow test

- RI2 :
  - gas started to percolate along borehole wall
- RI3:
  - Sudden drop in pressure at 90,9 bars
  - Correlated with a slight peak in packer pressure PPK01
    - This suggests abrupt detachment at an interface along the borehole wall
- RI4 & RI5:
  - interferences are observed surrounding the packers 01-03-04 and into the intervals 01-03-04
  - Difficult to increase the pressure
- RI7:
  - Fracturing occurred at 131 bars
  - Drop of 6 bars



PGZ3
PGZ3002 - slow test

- After RI2 and during RI3 : gas percolates along borehole wall
  - Interferences are observed surrounding the packers (01-03-04) and into the intervals (01-03-04)
- RI4 & RI5
  - The gas flow rate was increased to compensate for gas leakage along the borehole
    - Max injection rate: 90 mLn/min
    - Difficult to increase the pressure



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PGZ3
Summary

Fast injection flow rate (500 mLn/min) in PGZ1002 and PGZ1003

- a fracture was initiated and spread along borehole wall :
  - @ PGZ1002 : 12,78 MPa
  - @ PGZ1003 : 14,28 MPa
- A gas fracture was created with a gas pressure value well **above** the minimum principal stress component (~ 12.5 MPa)

Slow gas injection flow rate in PGZ3001 and PGZ3002

- Fracturing pressure was only reached in PGZ3002
  - 13.1 MPa
- It is difficult to increase the pressure in the testing interval
  - Gas could easily percolate along horizontal boreholes at low pressure

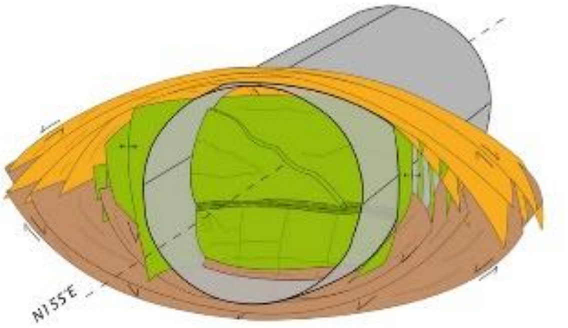
PGZ1 vs PGZ3
Where does the gas flow ?

In PGZ3 boreholes: gas easily percolates along borehole wall or within the BDZ

- Horizontal boreholes
  - Breakouts along borehole wall
    - No perfect circular cavity
    - Tightness between packers and rock
      - Water => YES due to self-sealing
      - Gas => No
    - Tightness between resin and rock
- It is very likely that gas percolates along the interfaces (packer-rock and resin-rock)

In PGZ1 (PGZ1201): no gas flows along borehole

- PGZ1201 is oriented // to sigma H but inclined
  - Less breakouts ?
    - Better gas tightness between packers and rock ?



Shape of the excavation damaged zone for drift oriented along sigma H

breakout along horizontal borehole (oriented sigma H) => cavity is not perfectly circular

Thank you for your attention

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