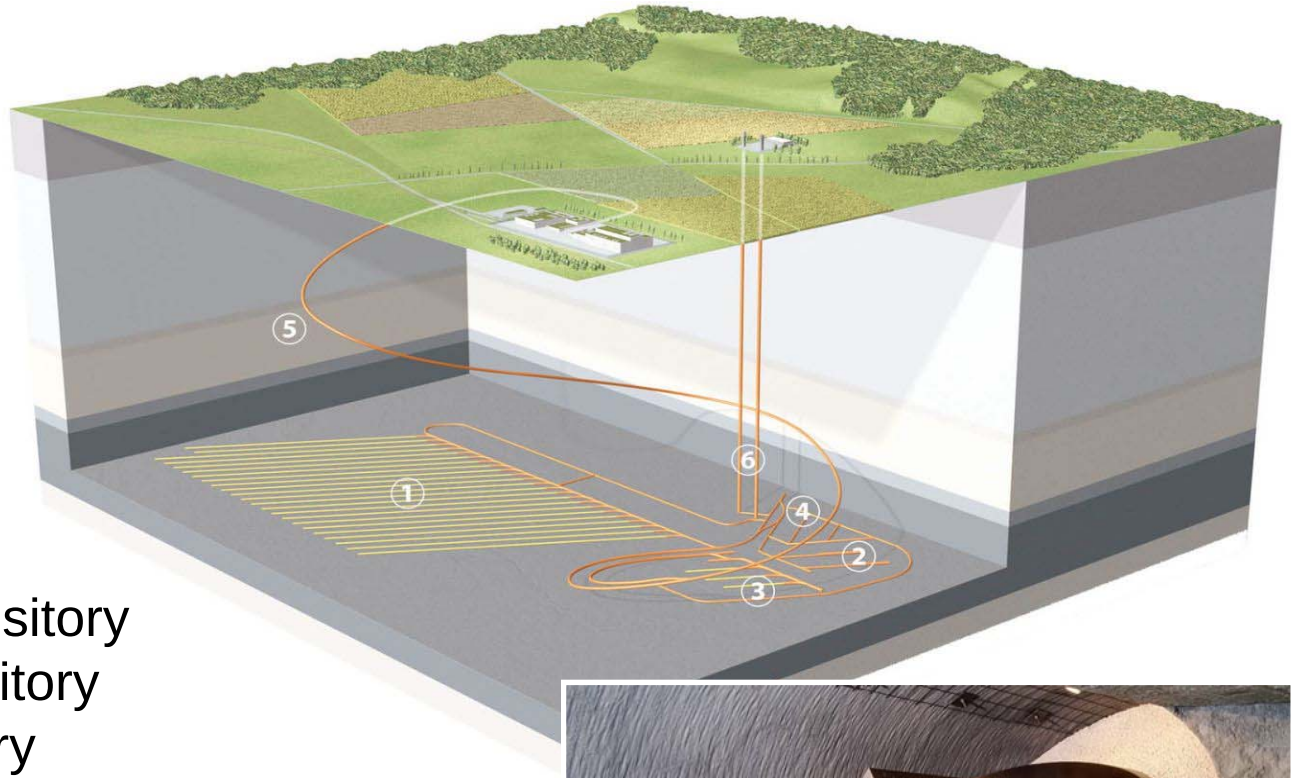
Enseignements tirés d’essais de chauffage in-situ dans des argilites

Benoit Garitte

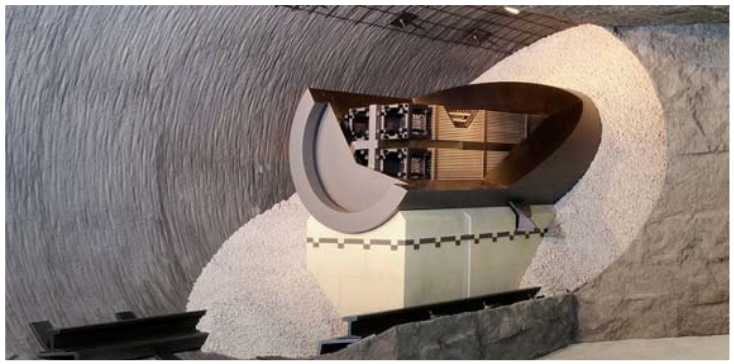
nagra.

Swiss concept for the HLW[1] repository

- **Monitored Geological Repository**



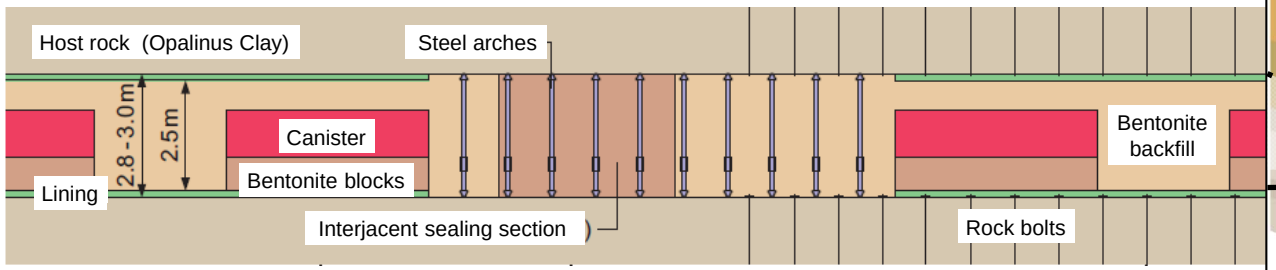
❶ HLW/SF repository
❷ LL-ILW repository
❸ Pilot repository
❹ Test area (rock laboratory)
❺ Access tunnel
❻ Ventilation and construction shafts

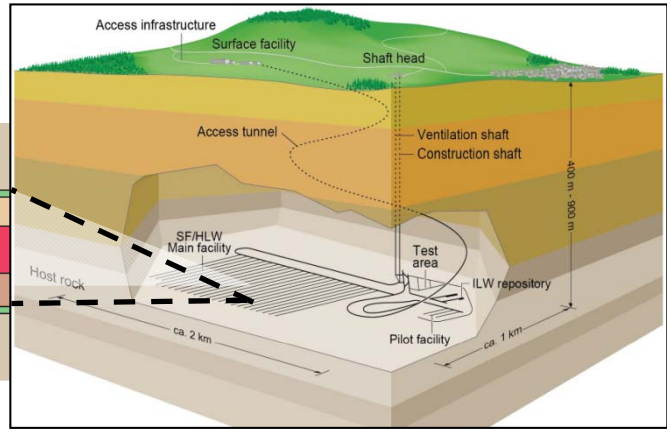


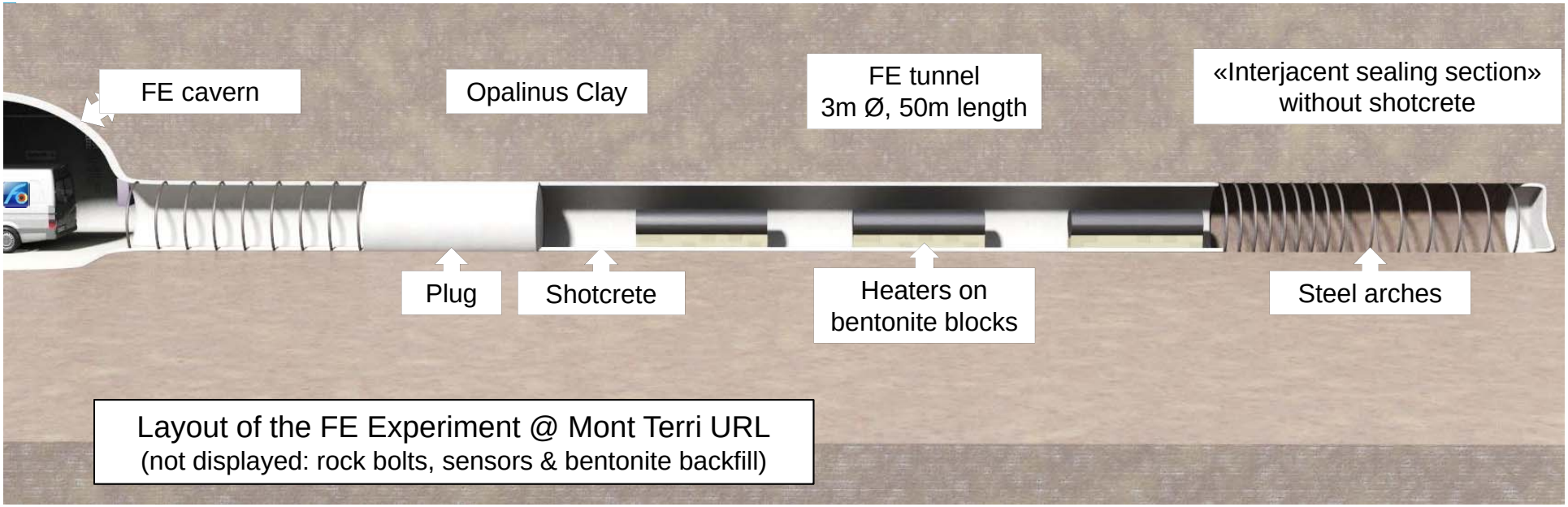
High-level radioactive waste, spent fuel and long-lived intermediate level radioactive waste

Full-Scale Emplacement (FE) Experiment

- Designed according to the Swiss concept for spent fuel (SF) / high-level waste (HLW) emplacement tunnel

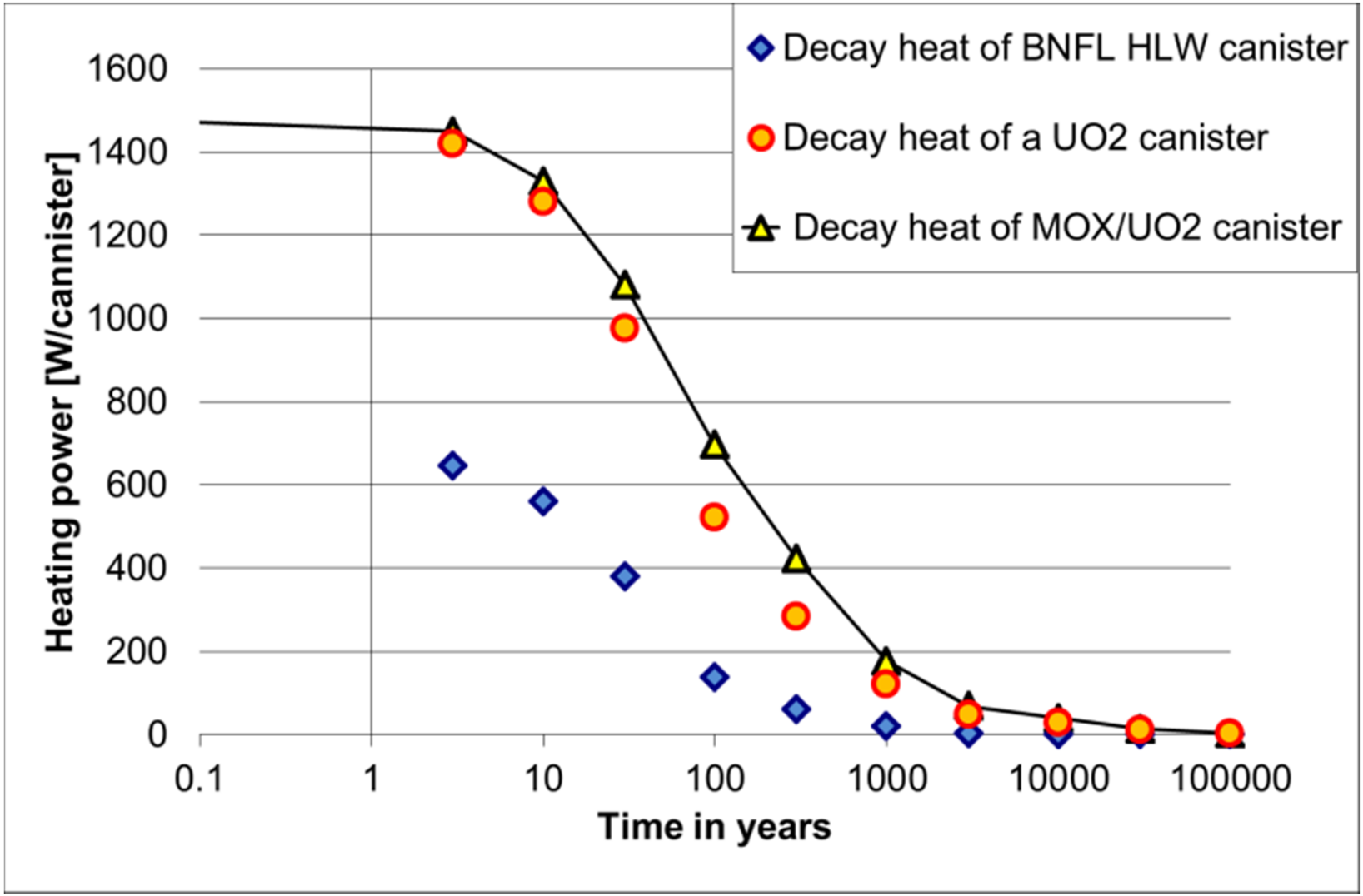






Layout of the FE Experiment @ Mont Terri URL
(not displayed: rock bolts, sensors & bentonite backfill)

Radioactive waste heat release



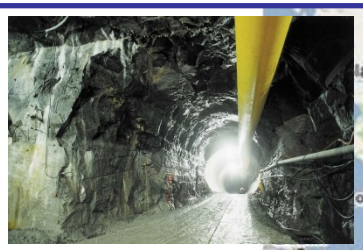
Index

Note beforehand: many of the results presented herein come from my “previous” life. The measurements are mainly due to ANDRA and the TIMODAZ and PEBS projects.

- Introduction
- Small scale experiments (HE-D, TER, TED and ATLAS)
  - Measurements
  - Modelling of the temperature field
  - Modelling of the pore water pressure field
- Larger and real scale experiments
  - HE-E
  - FE

URLs in Europe

Granite (Aspo)
200m – 450 m deep
Generic, purpose-built



Boom (plastic) clay (Mol)
230m deep
Generic, purpose-built

Opalinus (hard) clay (Mt Terri)
400m deep
Generic, not purpose-built

Rock salt (Asse)
490m – 800m deep
Generic, not purpose-built

C-O argillite (hard) clay (Bure)
450m – 520 m deep
Site-specific

Granite (Grimsel)
450m deep
Generic, not purpose-built

Argillaceous rocks

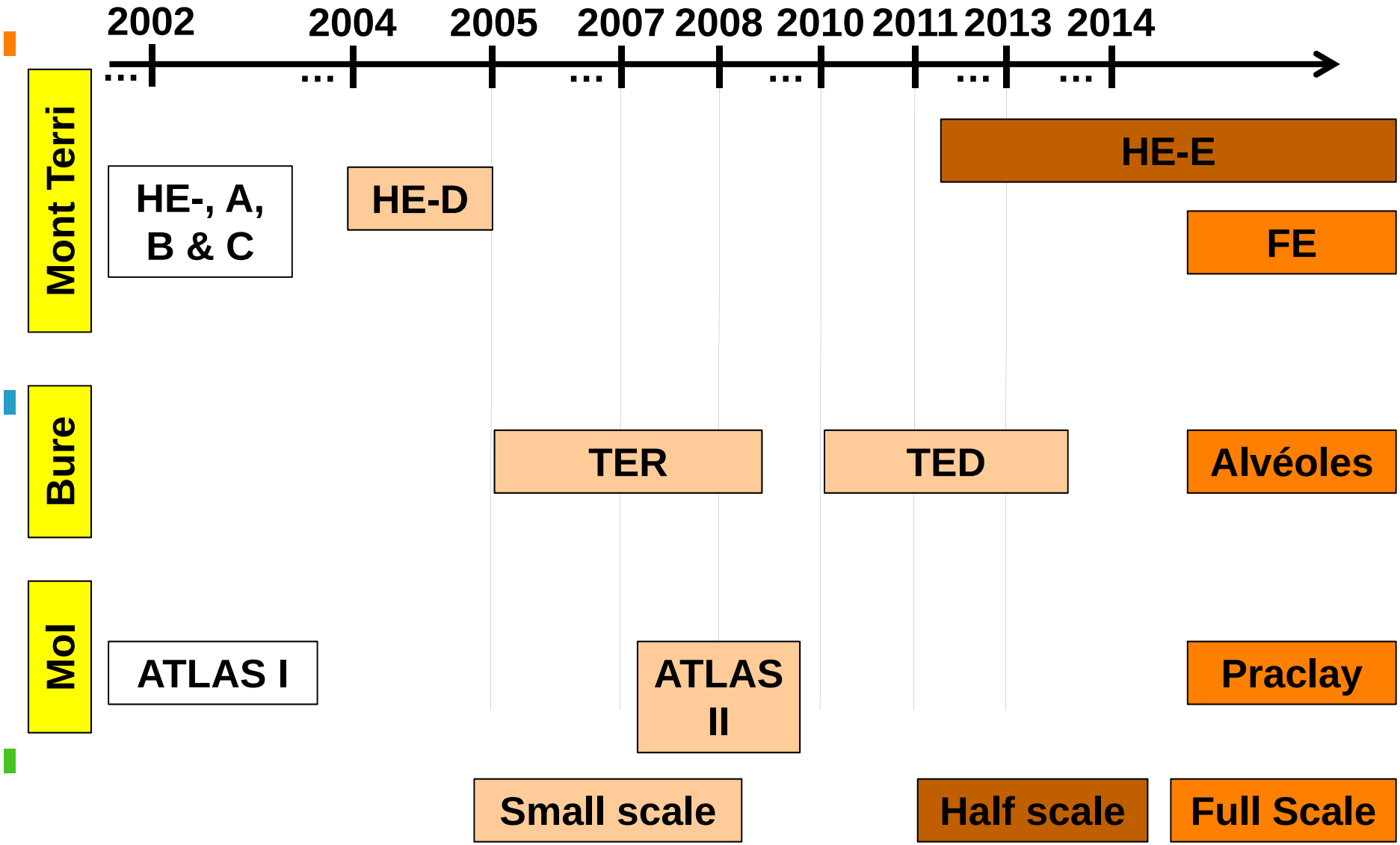
	Indurated clays		Plastic clays
	Callovo-Oxfordian mudstone	Opalinus clay	Boom clay
Dry density (g/cm^3)	2.21 – 2.33	2.22 - 2.33	1.61 – 1.78
Calcite content (%)	23 - 42	6 - 22	0 - 3
Porosity (%)	< 13	13.5 - 17.9	> 30
Water content (%)	< 5.5	4.2 - 8.0	> 9.5
Young's modulus (MPa)	4000 - 5600	4000 - 10000	200 - 400
UCS (MPa)	20 - 30	4 - 22	2
Permeability (m/s)	1 – 5x10^{-13}	1 – 5x10^{-13}	2 – 4.5x10^{-12}
Thermal cond. (W/mK)	1.6 – 2.8	1.2 – 1.7	1.3 – 1.7
Geological age (million years)	Callovo-Oxfordian (Mid.–Up. Jurassic) 155.7 – 163.7	Aalenian (Middle Jurassic) 171.6 – 175.6	Rupelian (Oligocene) 28.4 – 33.9

- Most relevant properties (thermal conductivity, permeability, stiffness, strength) are anisotropic

Gens et al. (2007)

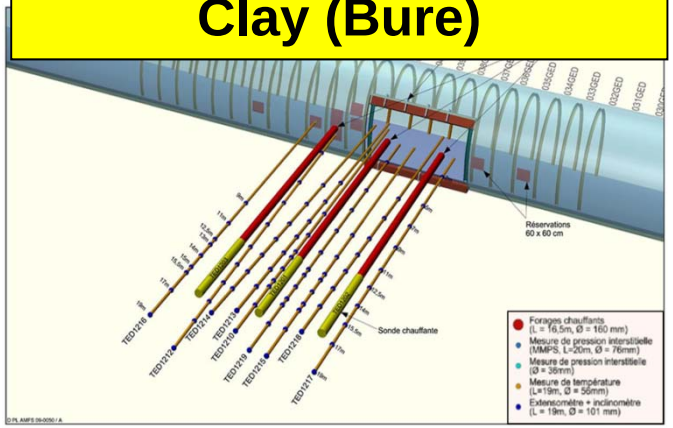
nagra.

Heating tests in argillaceous rocks

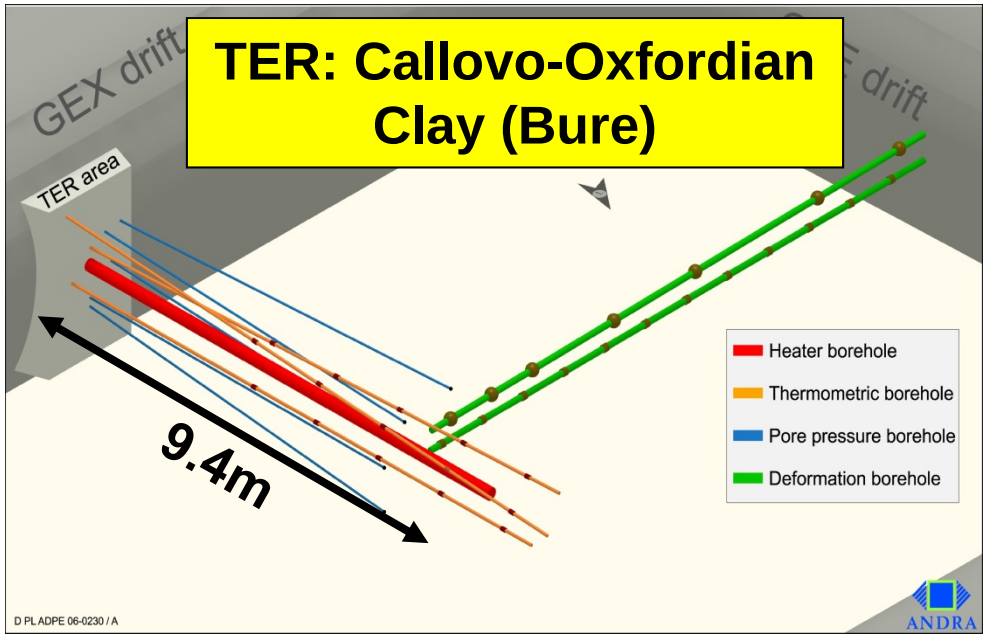


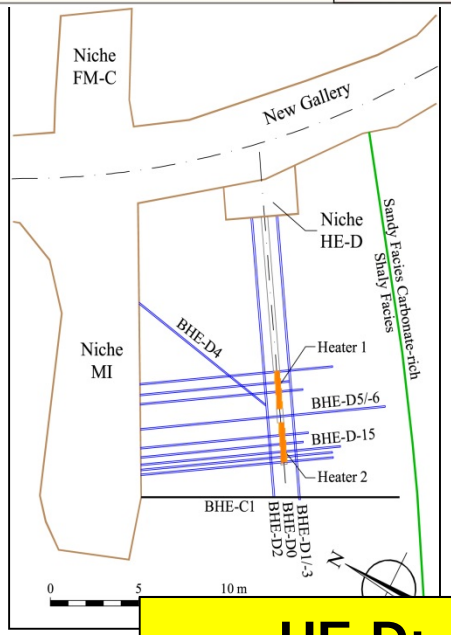
Small scale experiments

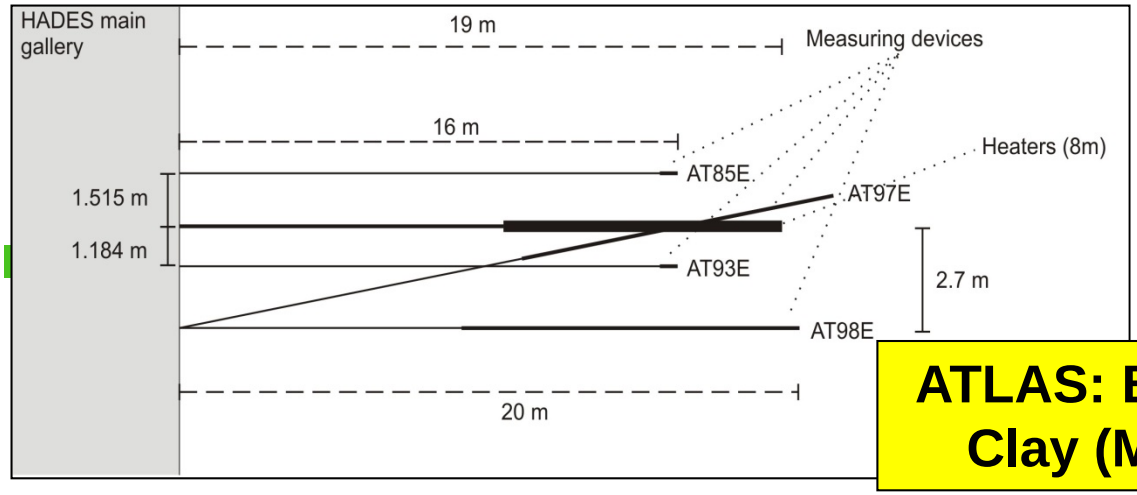
TED: Callovo-Oxfordian Clay (Bure)



TER: Callovo-Oxfordian Clay (Bure)



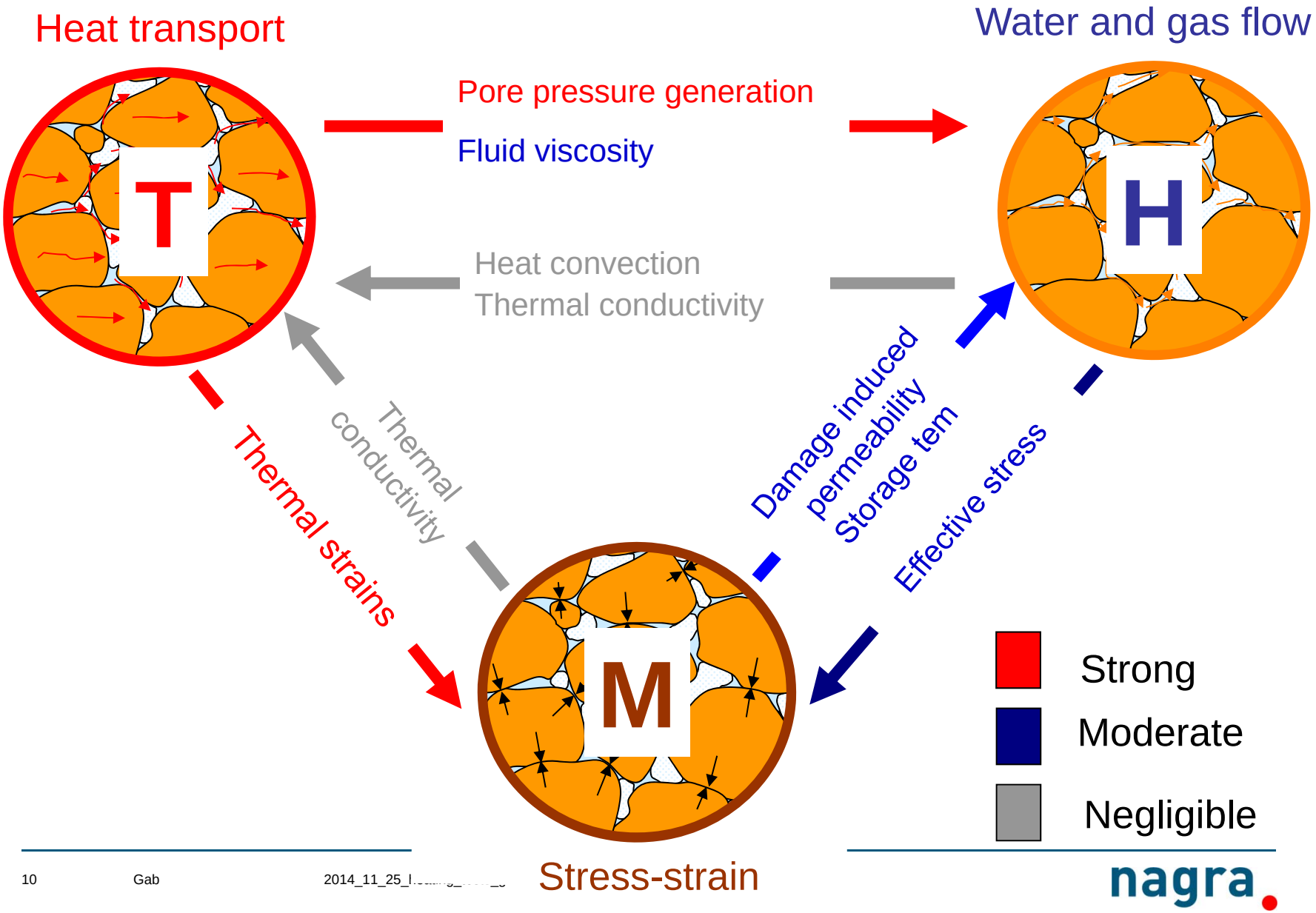




ATLAS: Boom Clay (Mol)

HE-D: Opalinus Clay (Mt Terri)

THM processes



nagra.

Determination of the thermal conductivity

- Under the following assumptions:
  - Saturated medium
  - Negligible porosity changes
  - Negligible convection
- = Thermal conduction problem

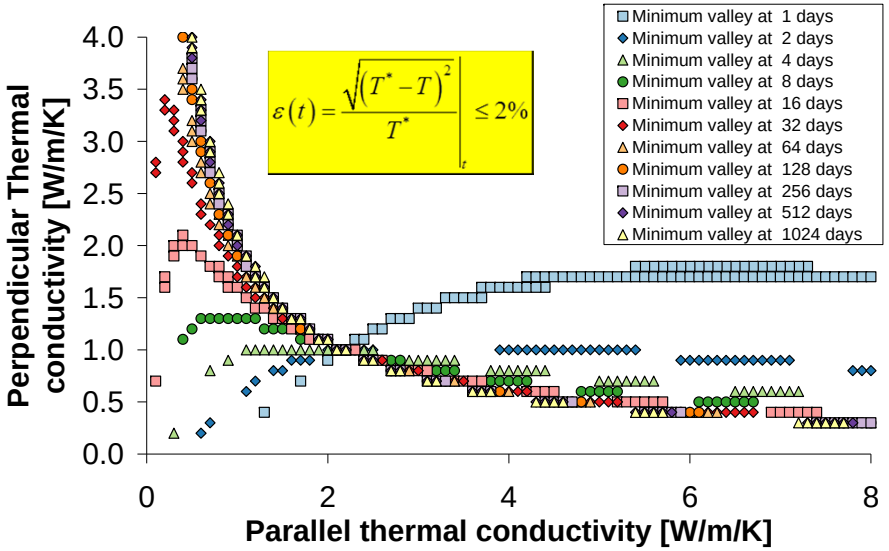
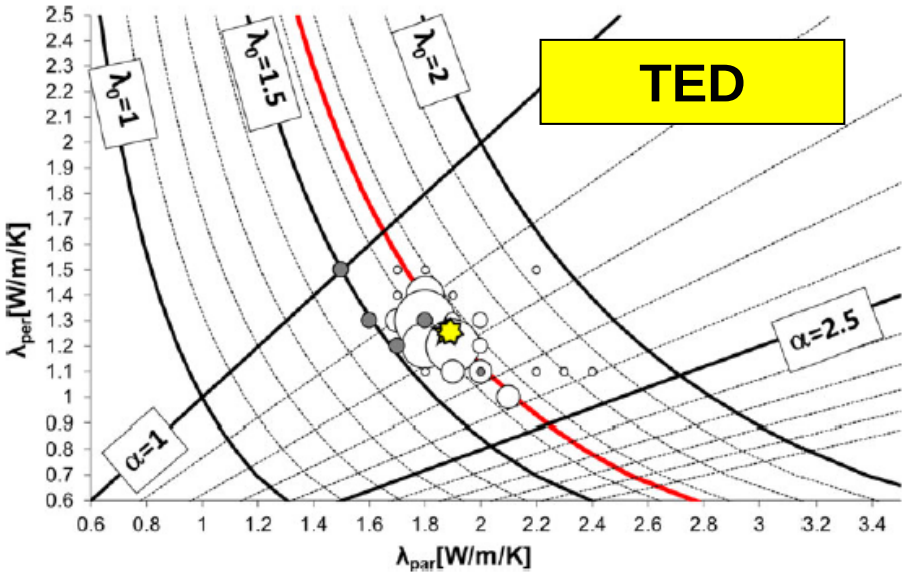


Table 2 Number of temperature sensors in the rock mass in the different in situ experiments

ATLAS	TER	TED	HE-D
24	20	108	26

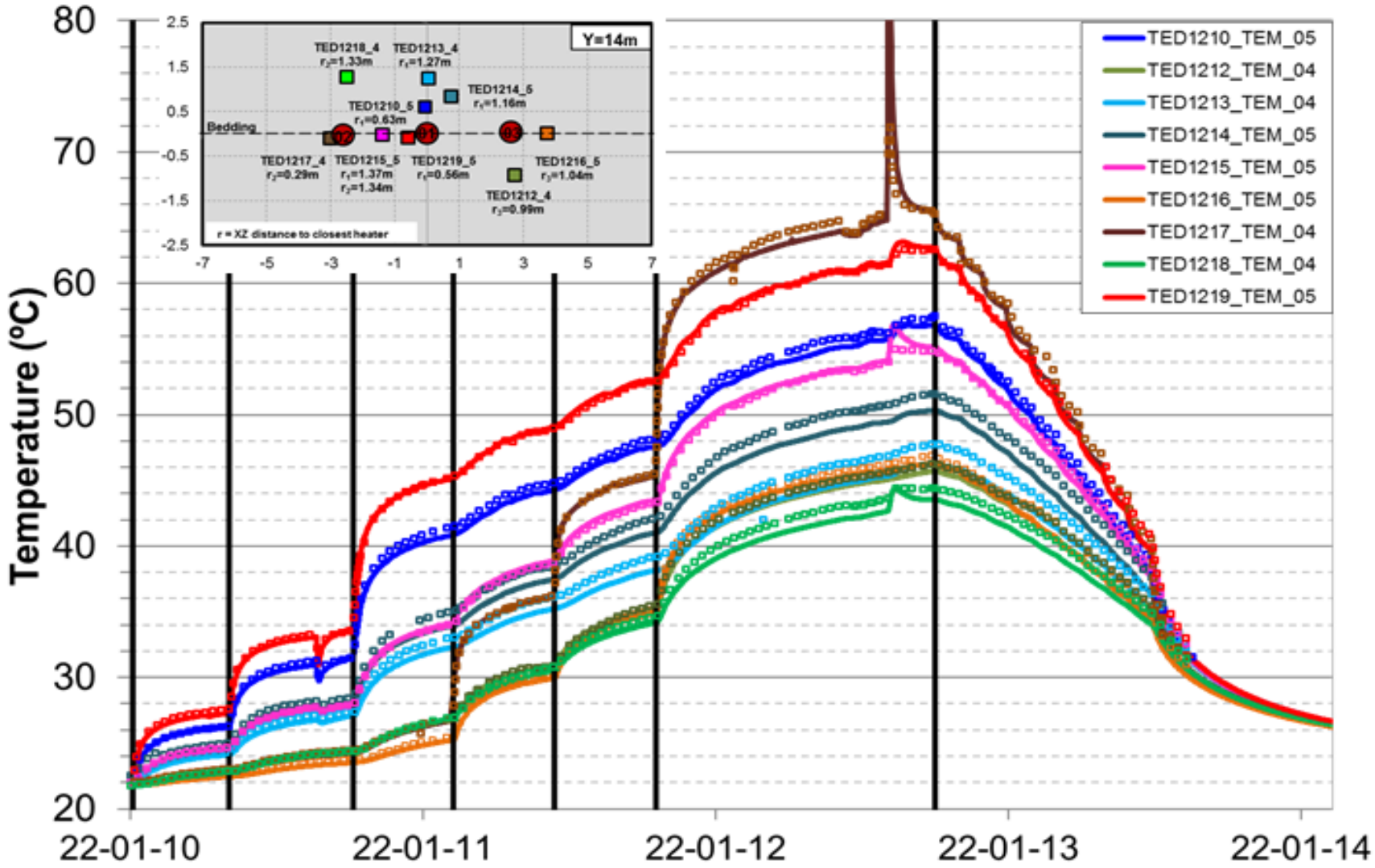
Table 8 Proposed reference thermal conductivity values for the three rocks

	λ_{par} (W/m/K)	λ_{per} (W/m/K)	λ_0 (W/m/K)	$\lambda_{par}/\lambda_{per}$
Boom Clay	1.55	1.06	1.35	1.46
Callovo-Oxfordian Clay	1.88	1.26	1.64	1.5
Opalinus Clay	2.15	1.2	1.8	1.8

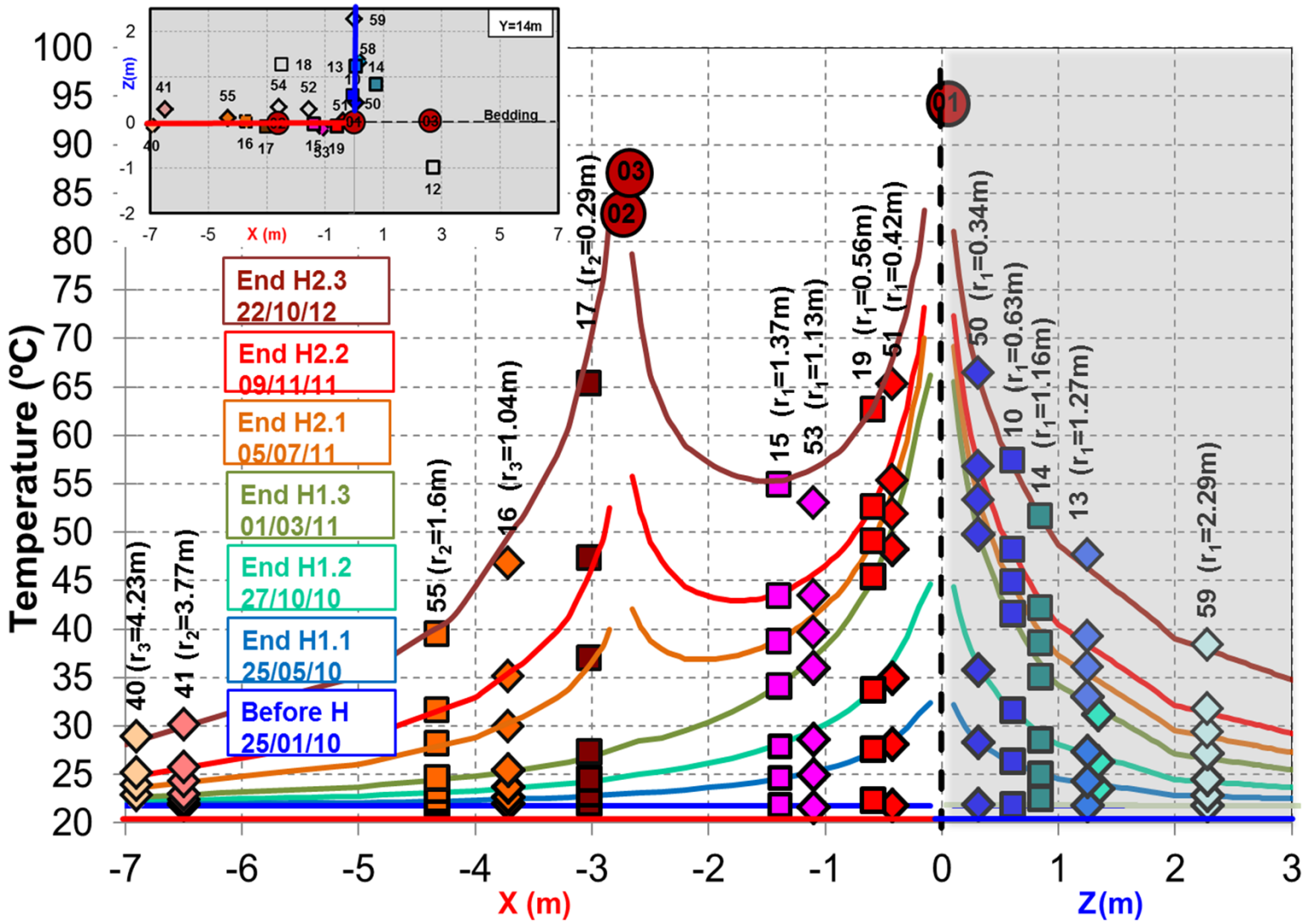


nagra.

TED: temperature evolution, middle plane

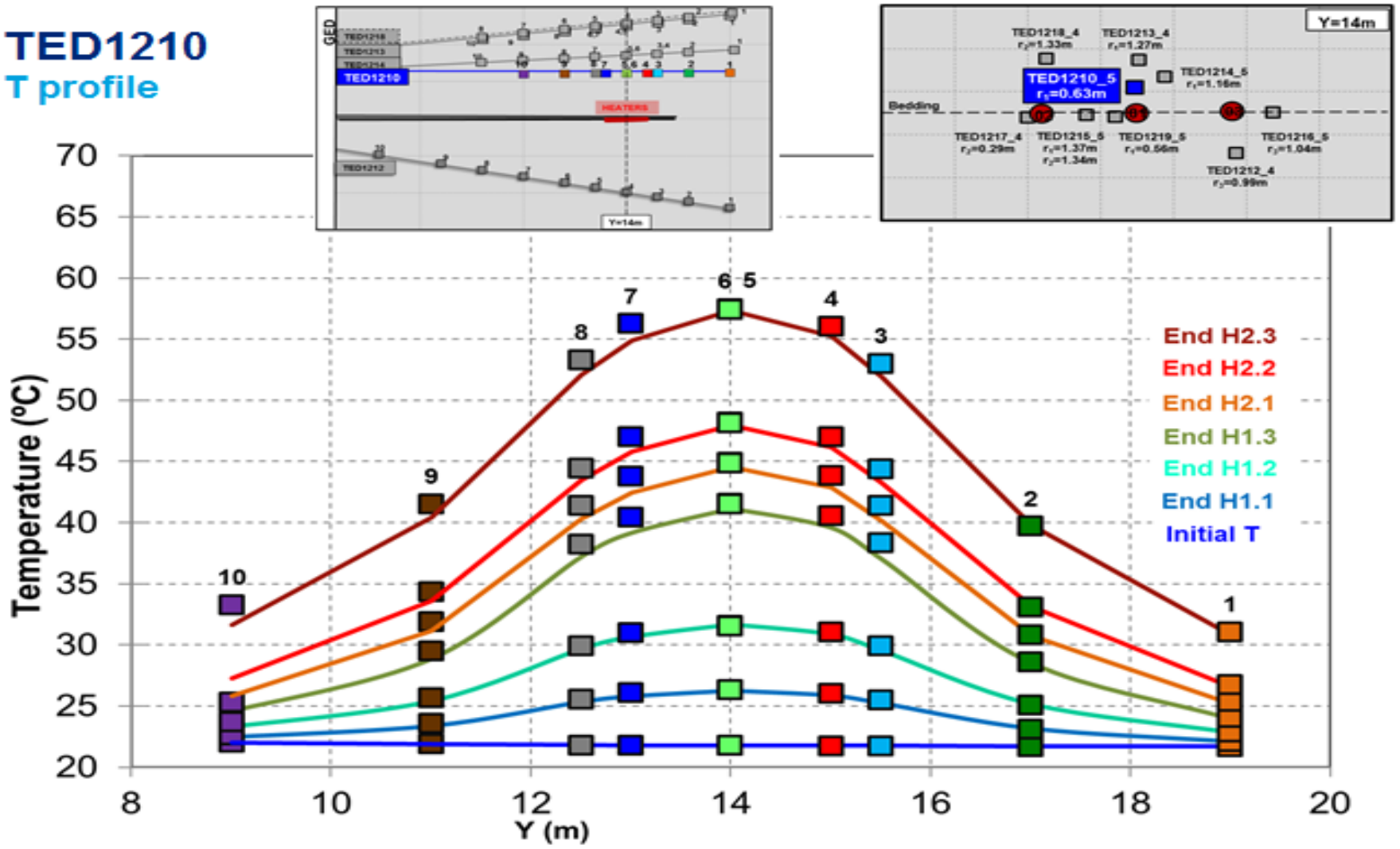


TED: temperature profiles. Middle plane



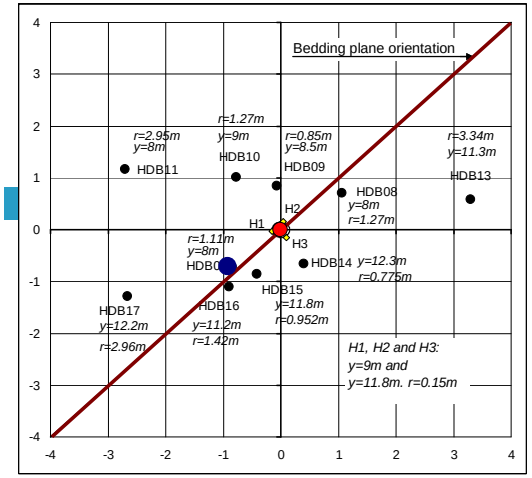
nagra.

TED: temperature profiles, one borehole

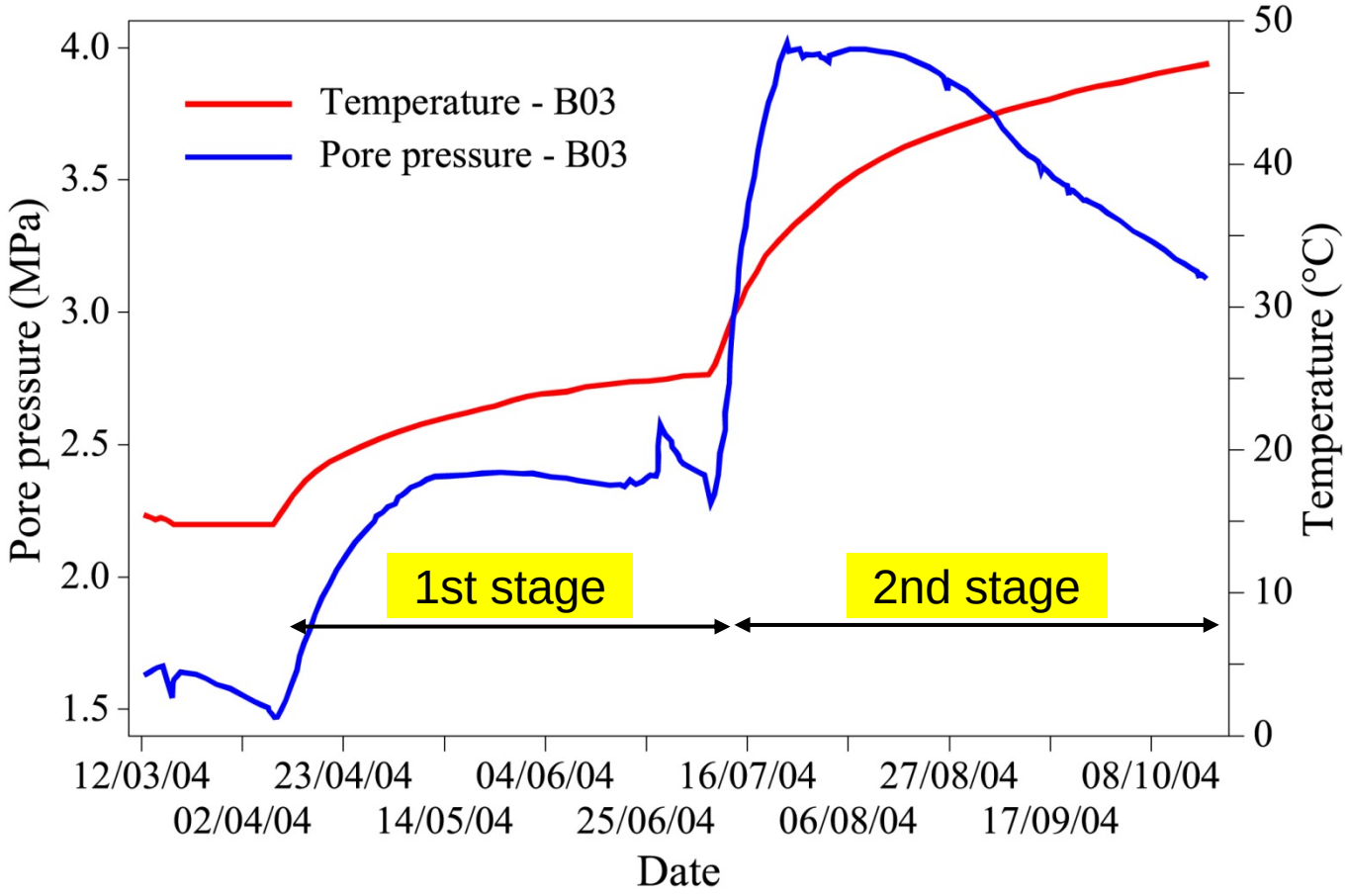


nagra.

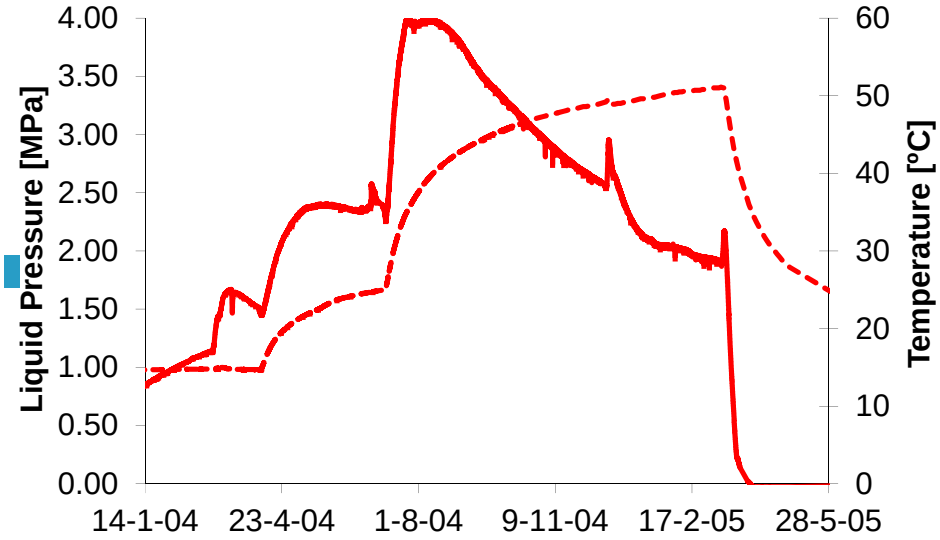
HE-D: TH coupling

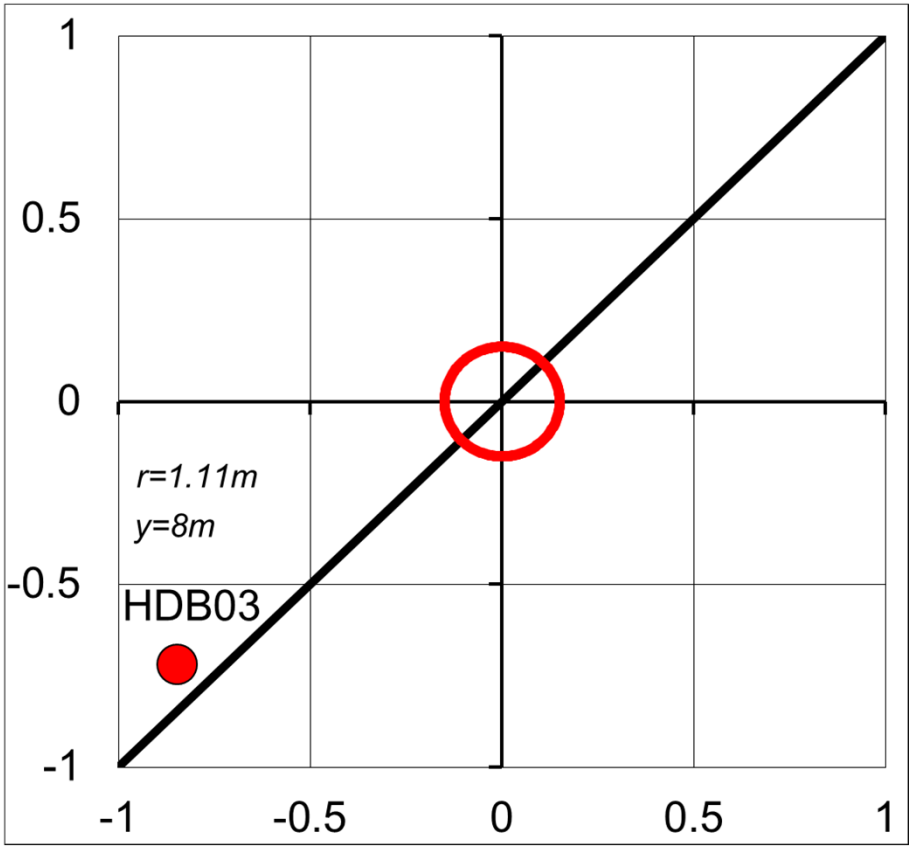


D03, r = 1.11 m
Parallel to bedding

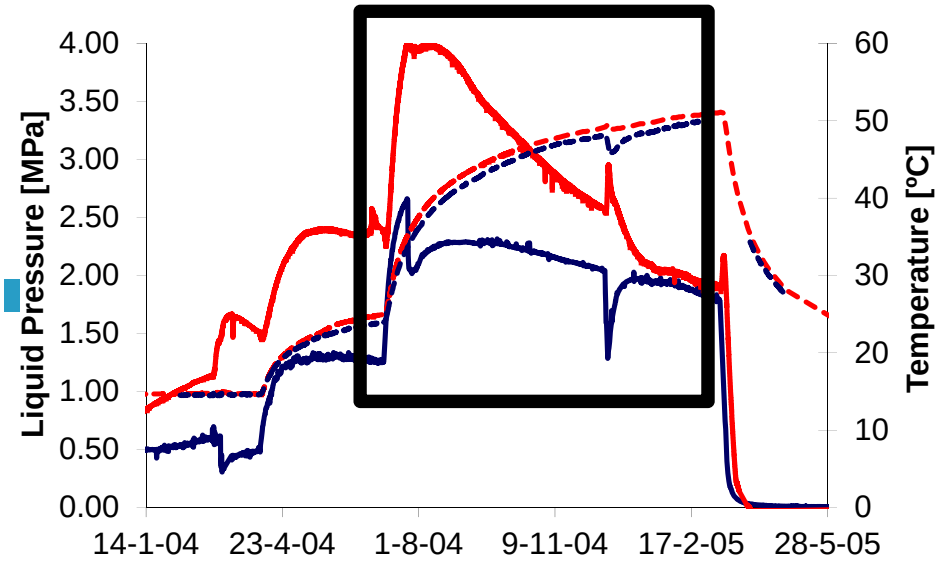


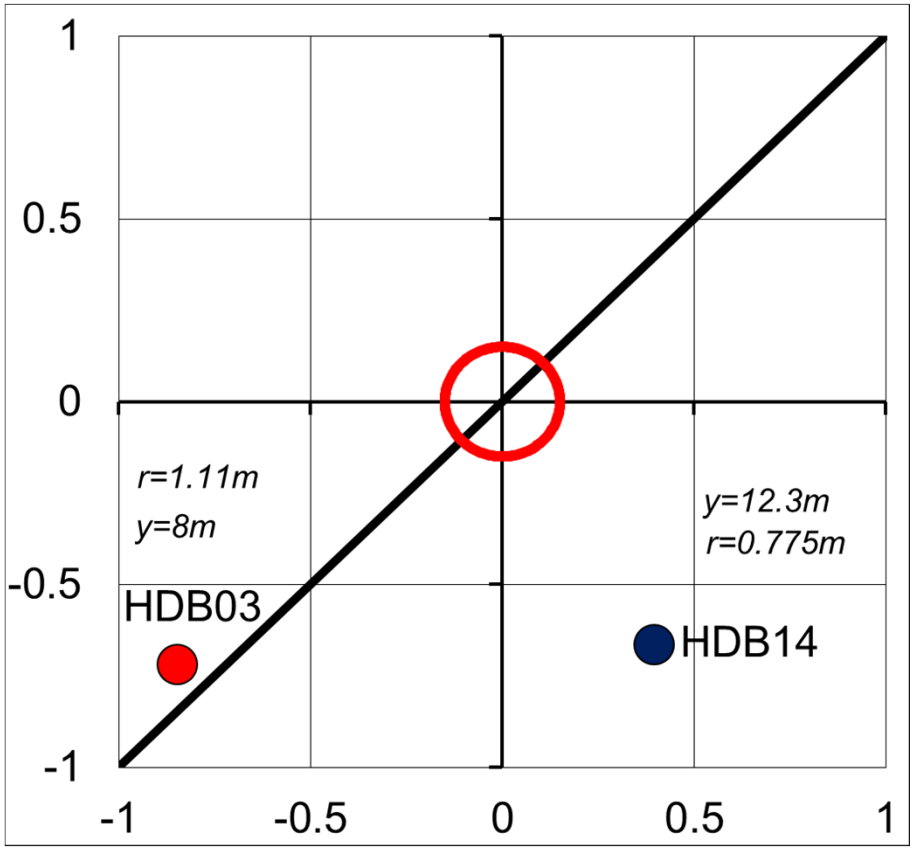
HE-D: TH coupling



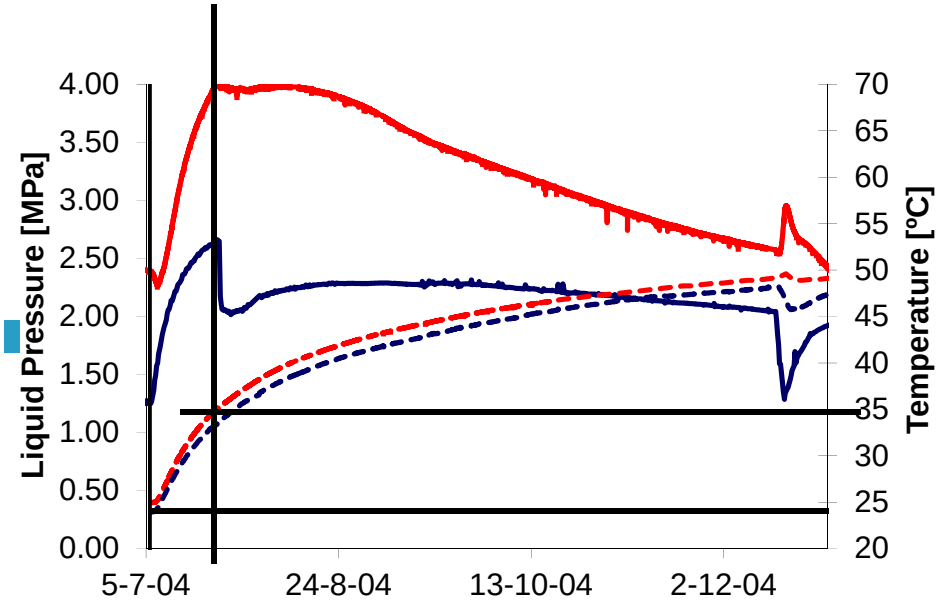


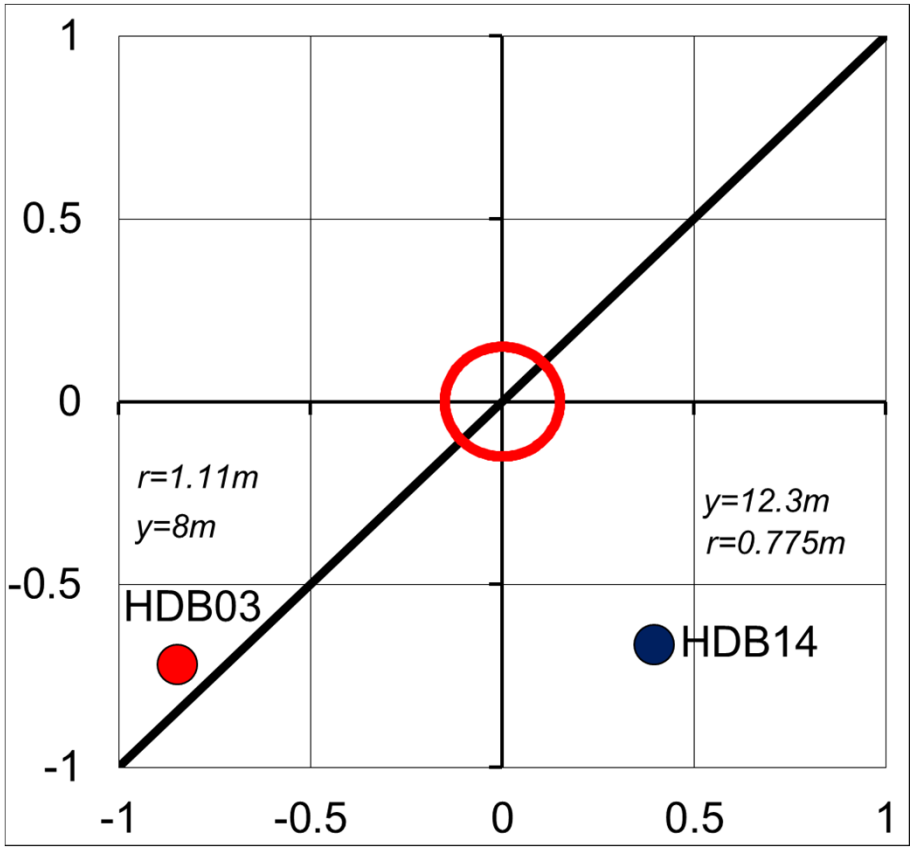
HE-D: TH coupling





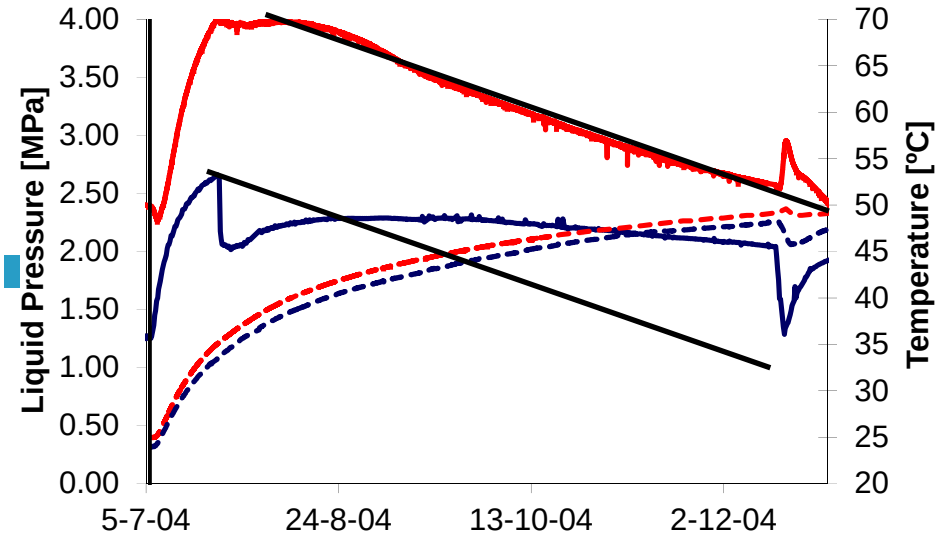
HE-D: TH coupling

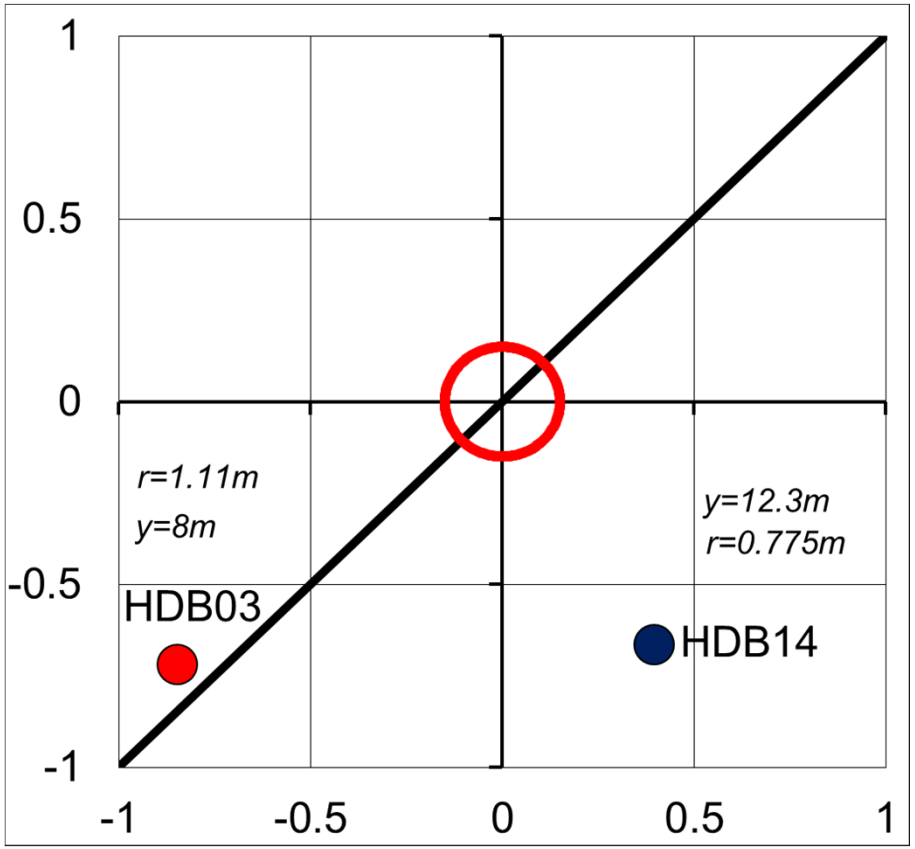




nagra.

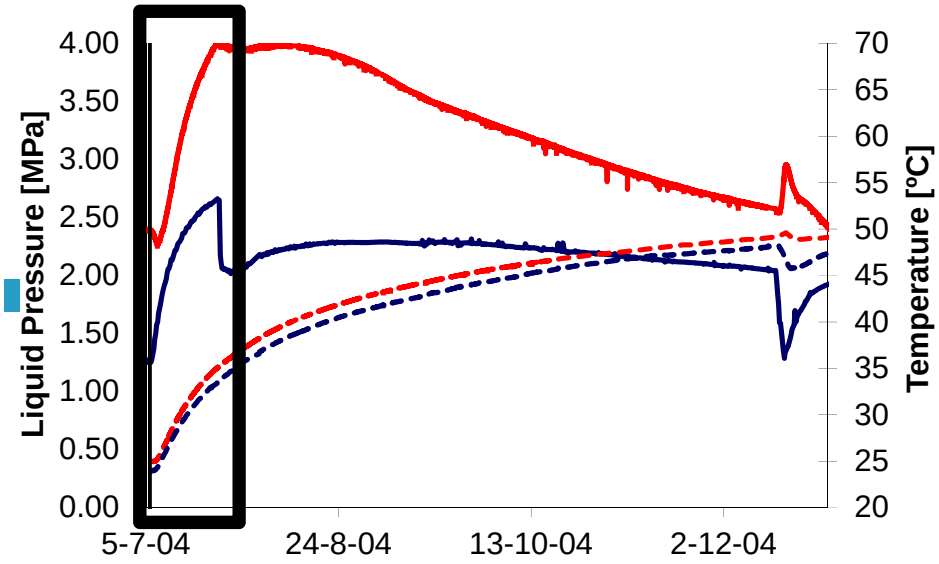
HE-D: TH coupling

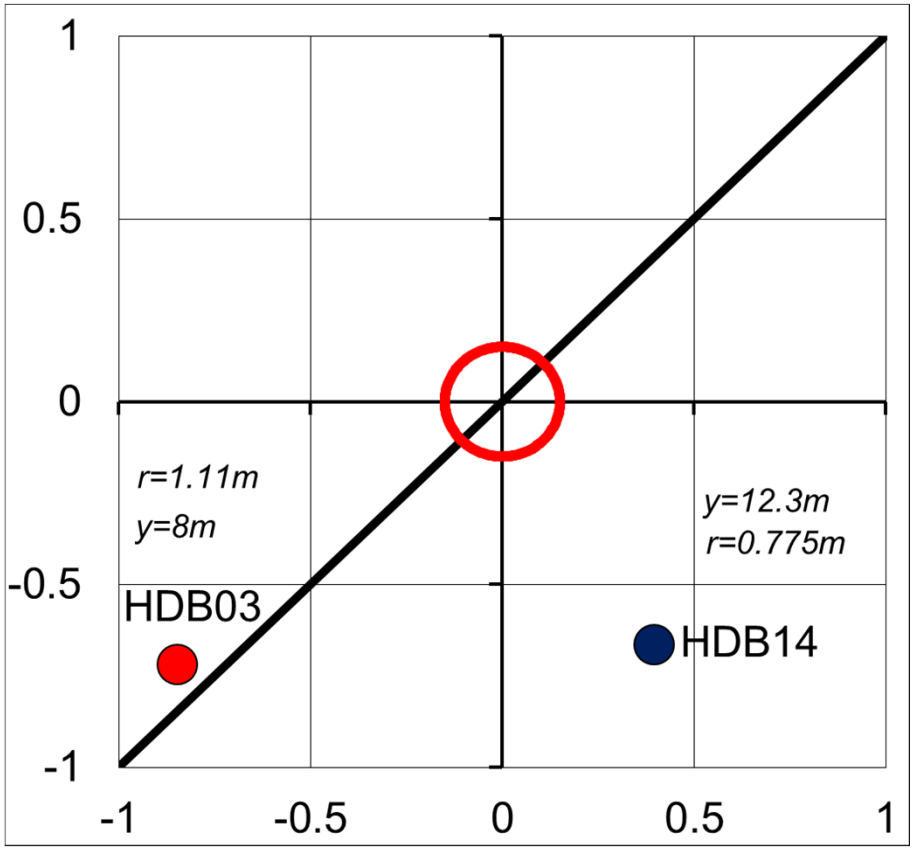




nagra.

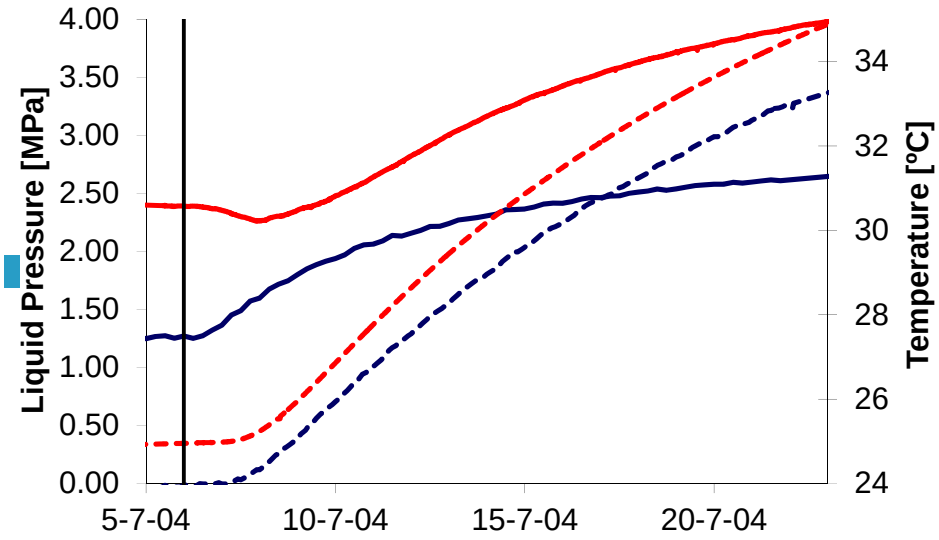
HE-D: TH coupling

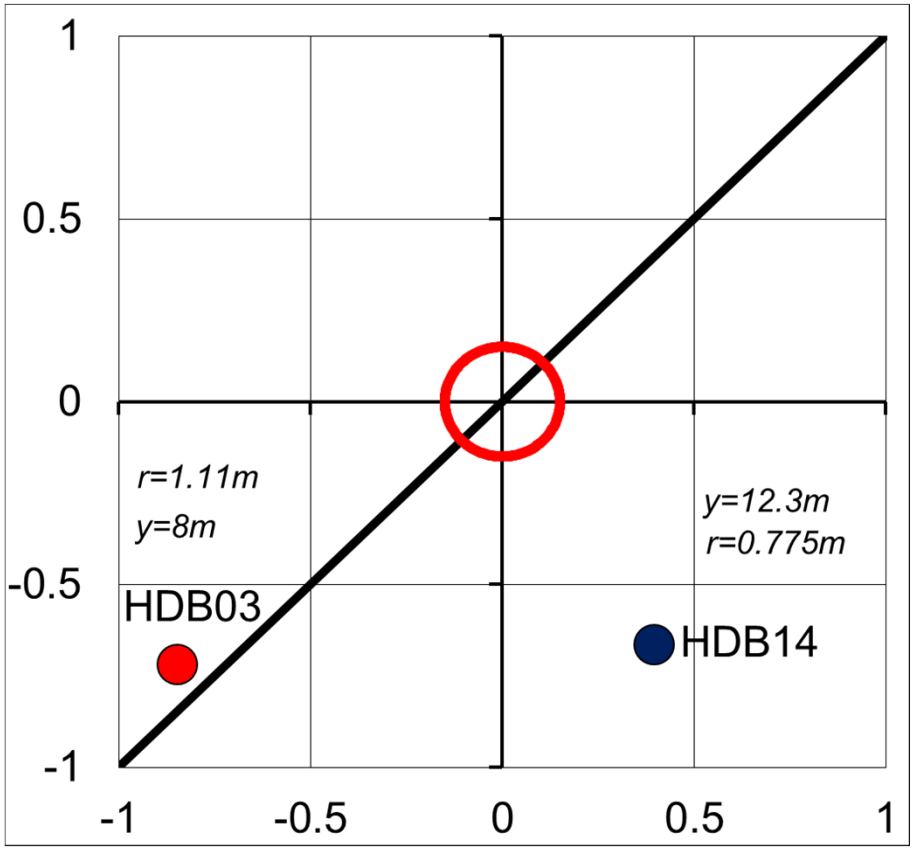




nagra.

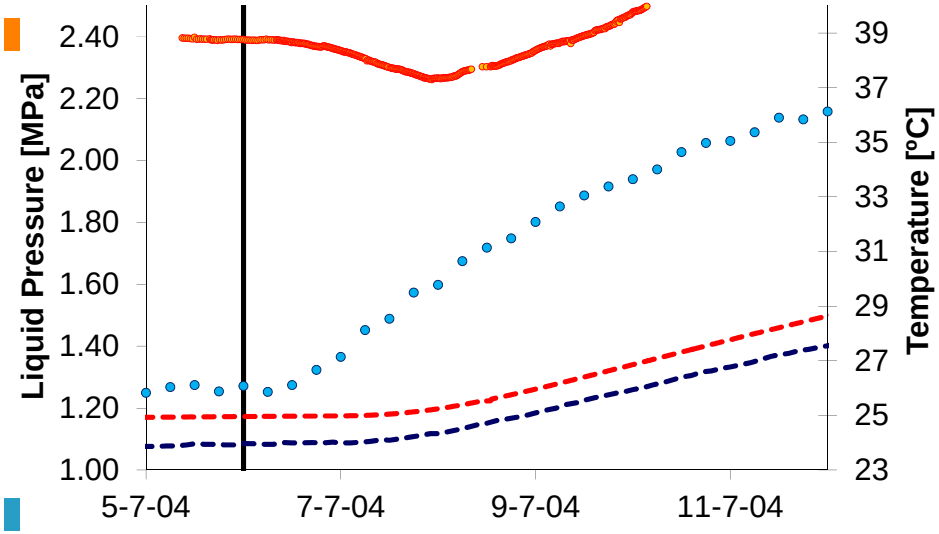
HE-D: TH coupling

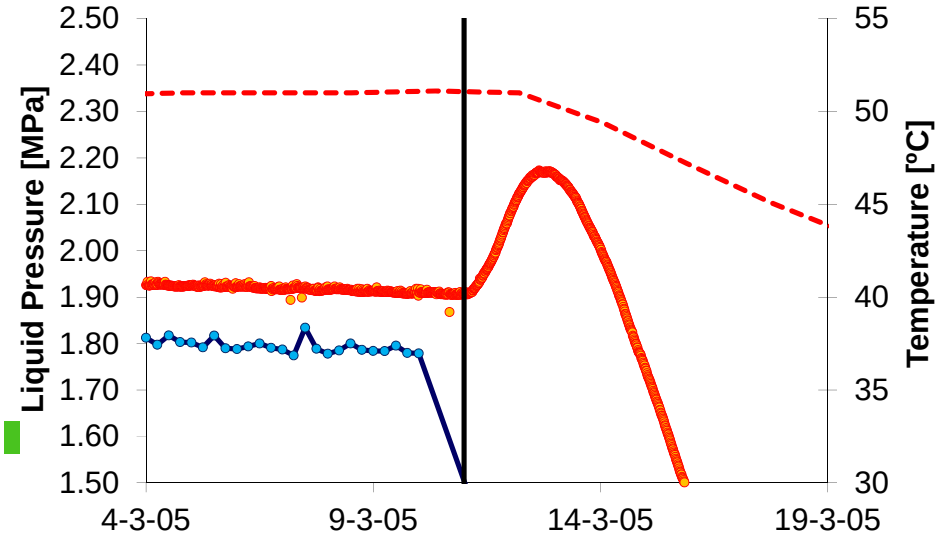


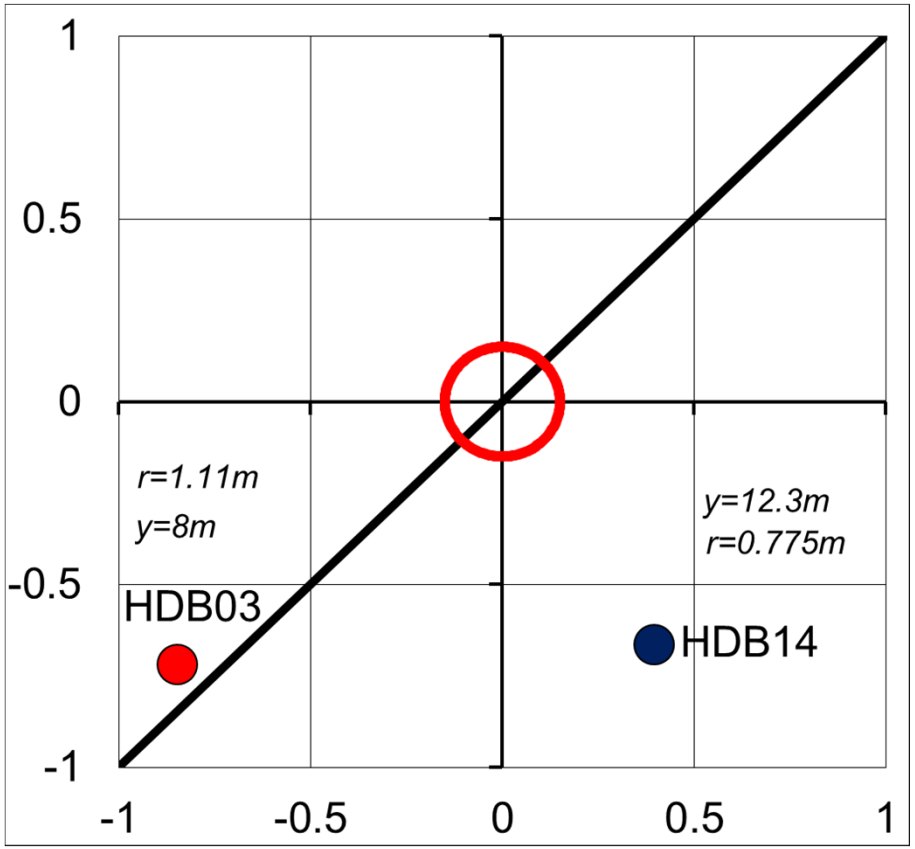


nagra.

HE-D: TH coupling

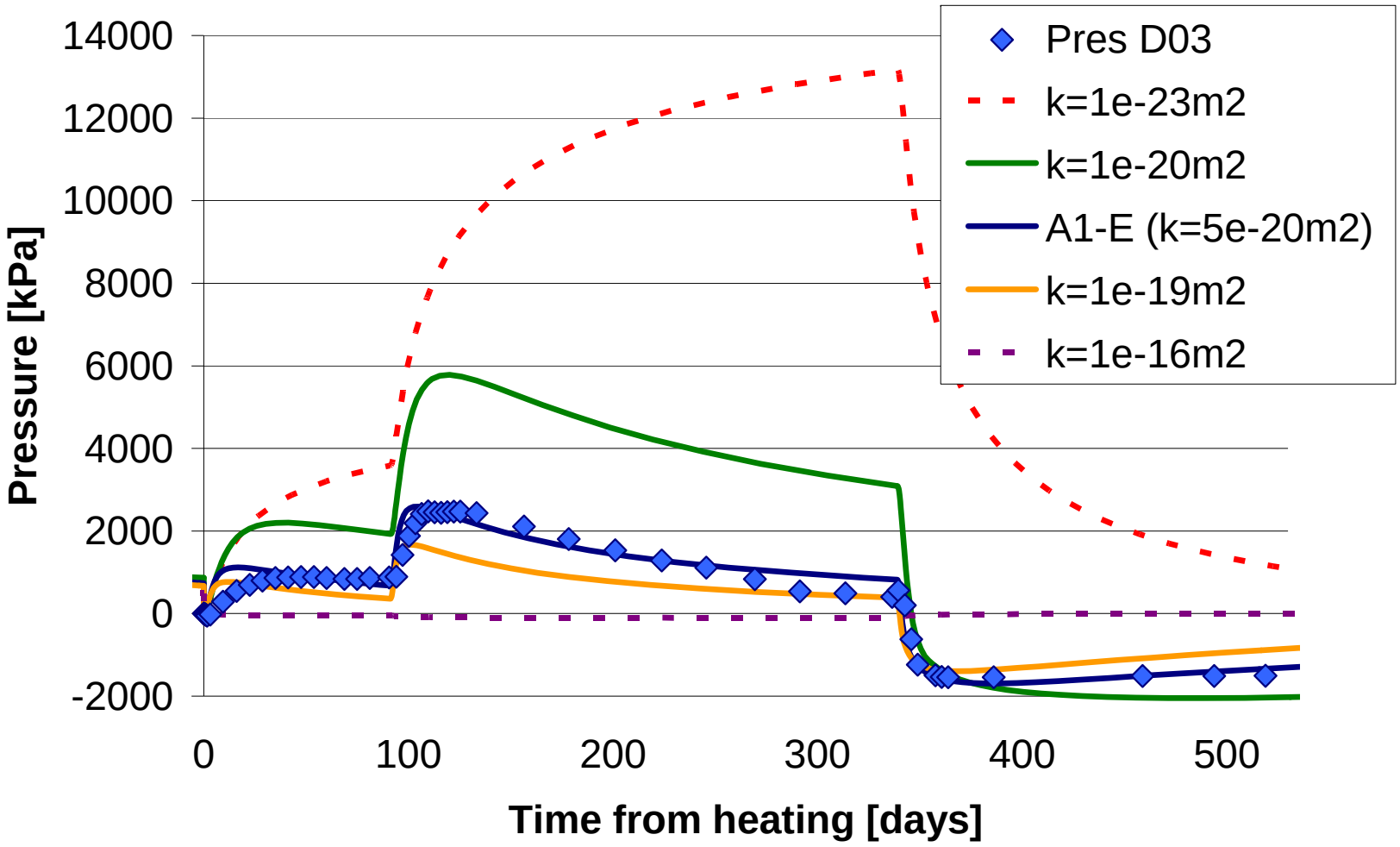






nagra.

HE-D: pore water pressure response



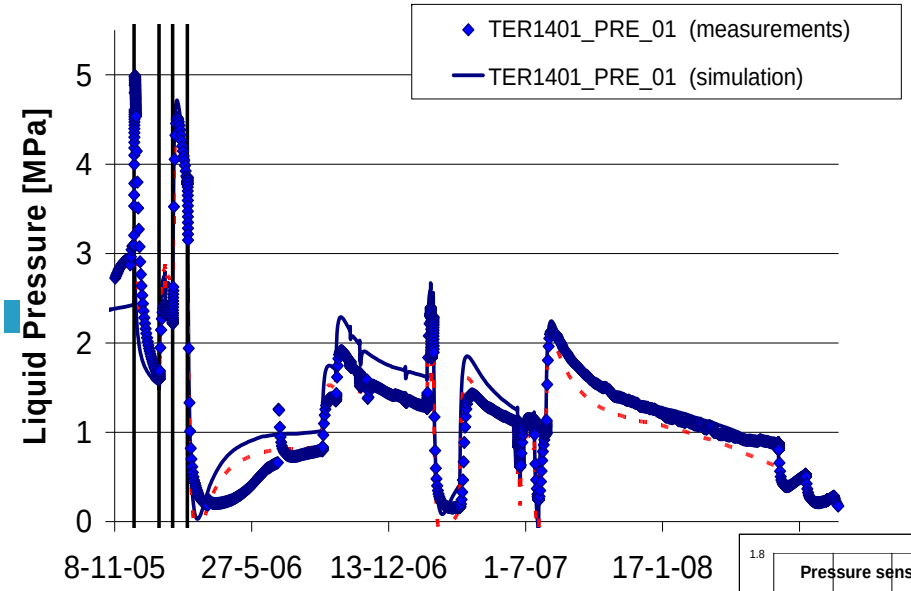
D03, r = 1.11 m

nagra.

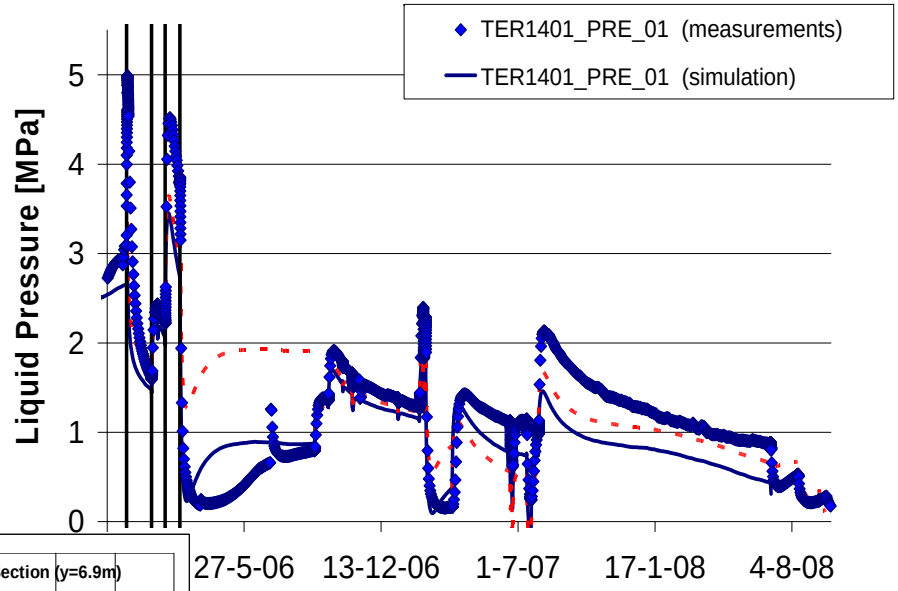
TER: pore water pressure response

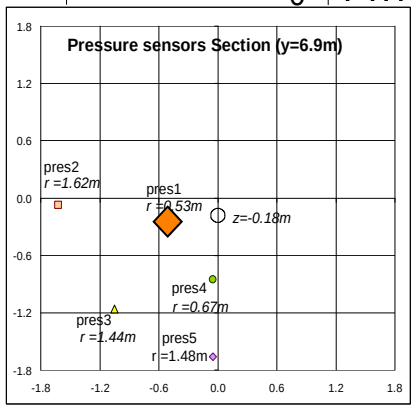
Measured and simulated pore water pressure evolution in the TER experiment

k=2.4E-20



k=4.8E-20

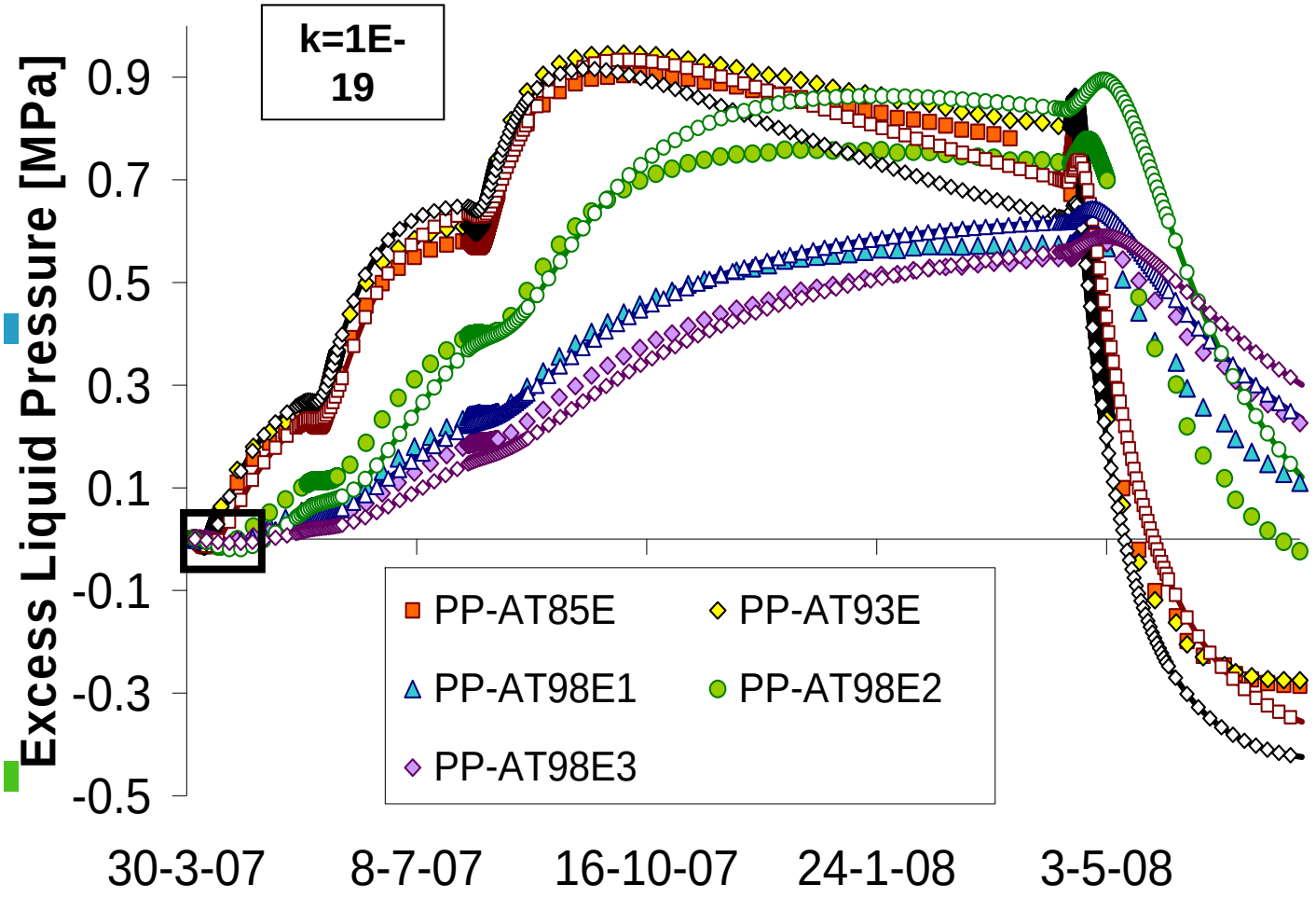




nagra.

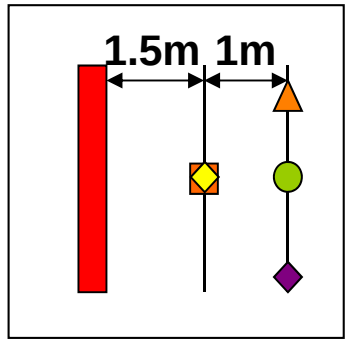
ATLAS: pore water pressure

Measured and simulated pore water pressure evolution in the ATLAS experiment



Measurements : coloured points

Simulation: blank points



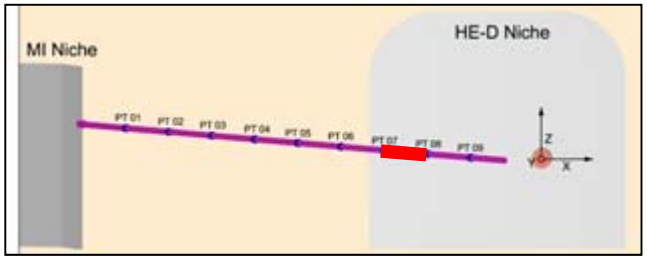
All sensors are in the bedding plane

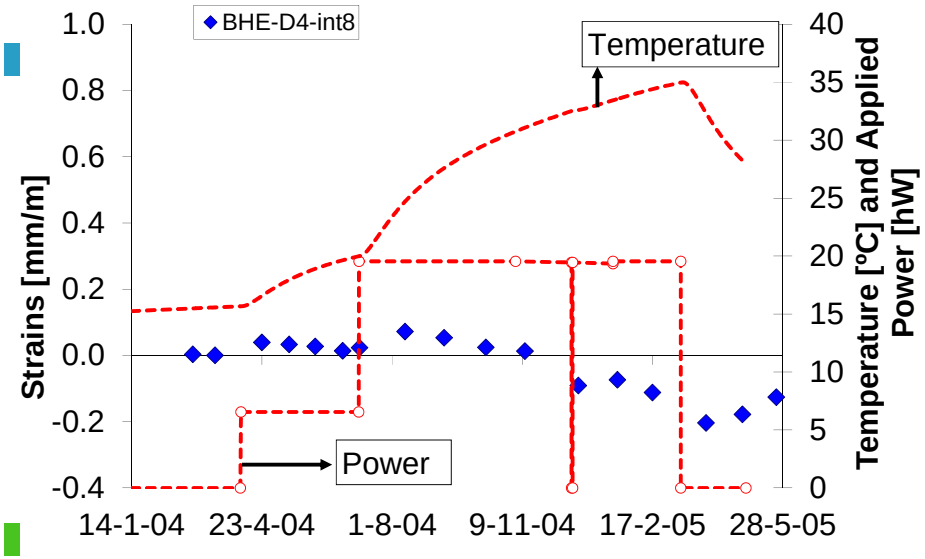
nagra.

HE-D: deformation measurements

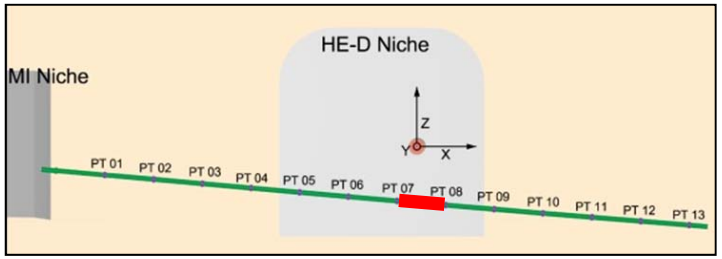
Deformation during heating

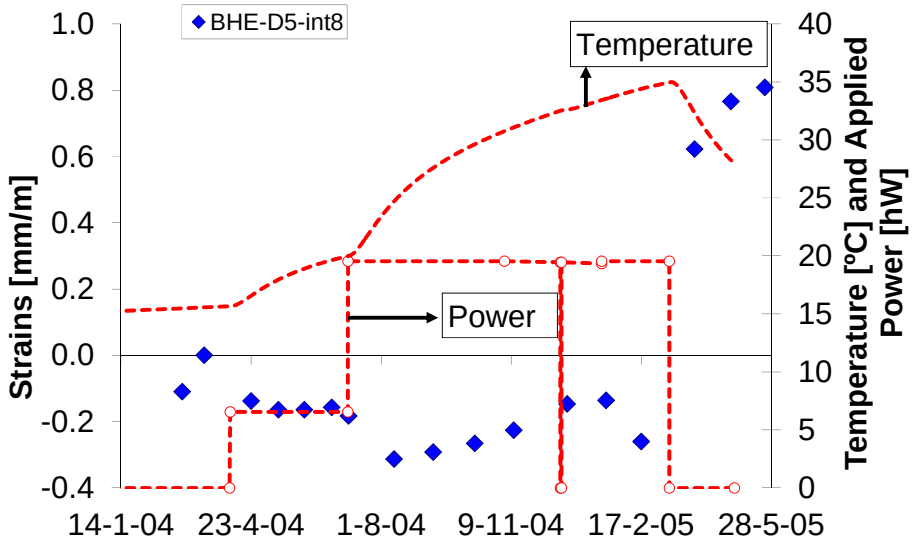
BHE-D04 | Radial





BHE-D05 | Circumferential



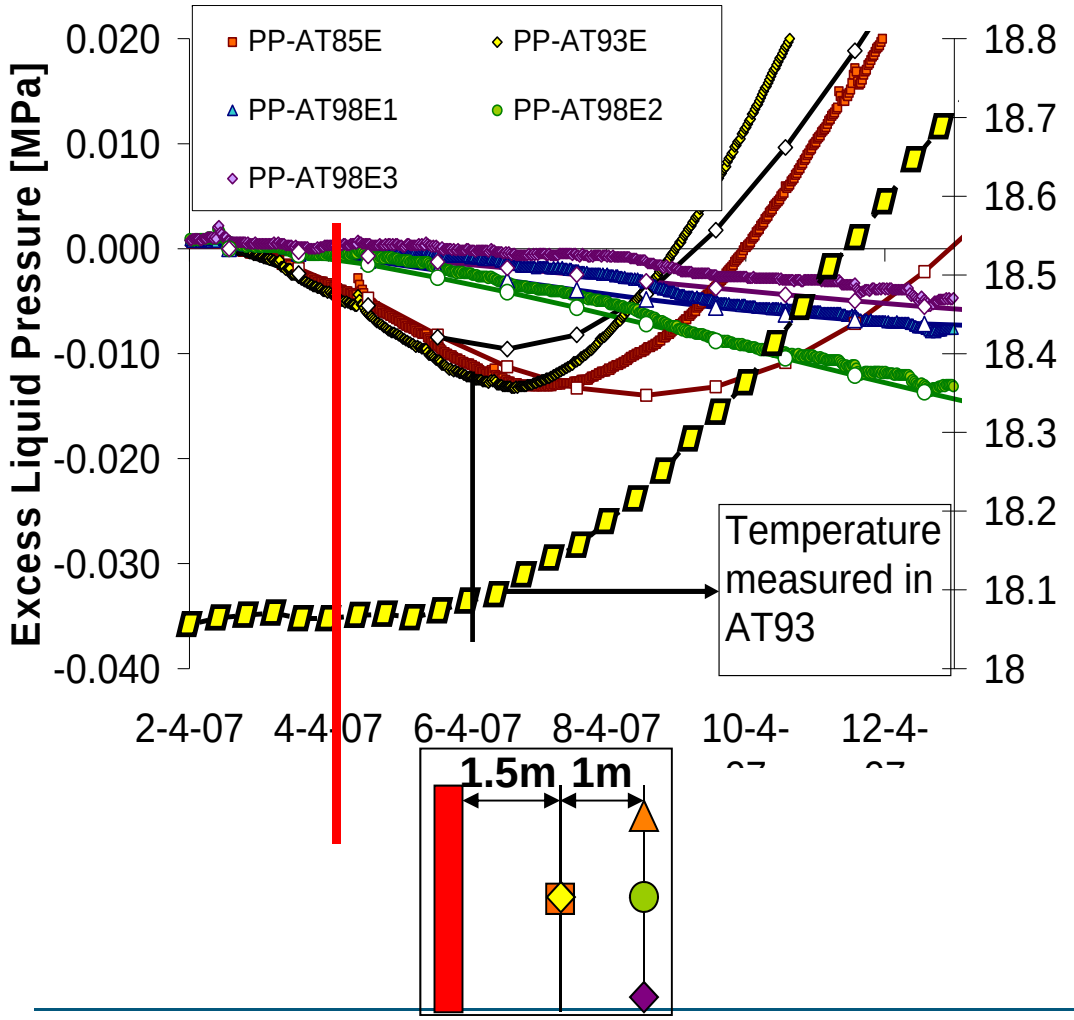


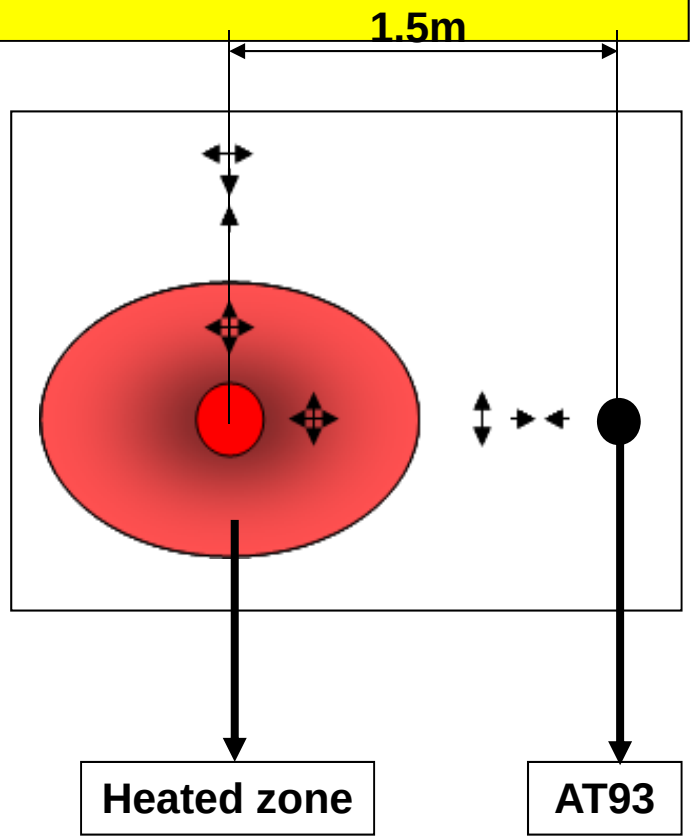
Positive is compression

nagra.

ATLAS: direct pore water pressure response

Measured and simulated pore water pressure evolution in the ATLAS experiment (10 first days)



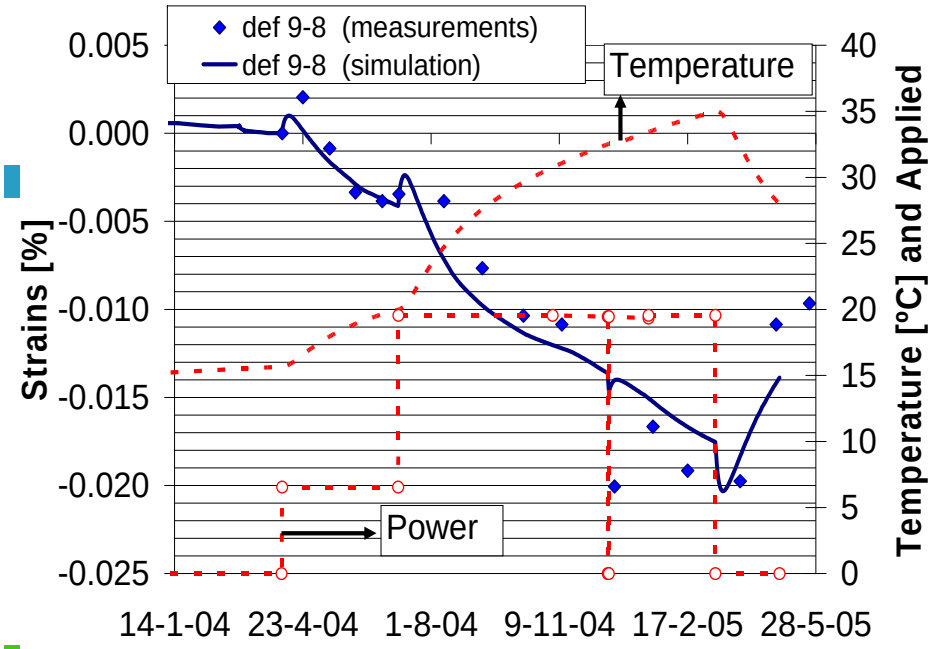


nagra.

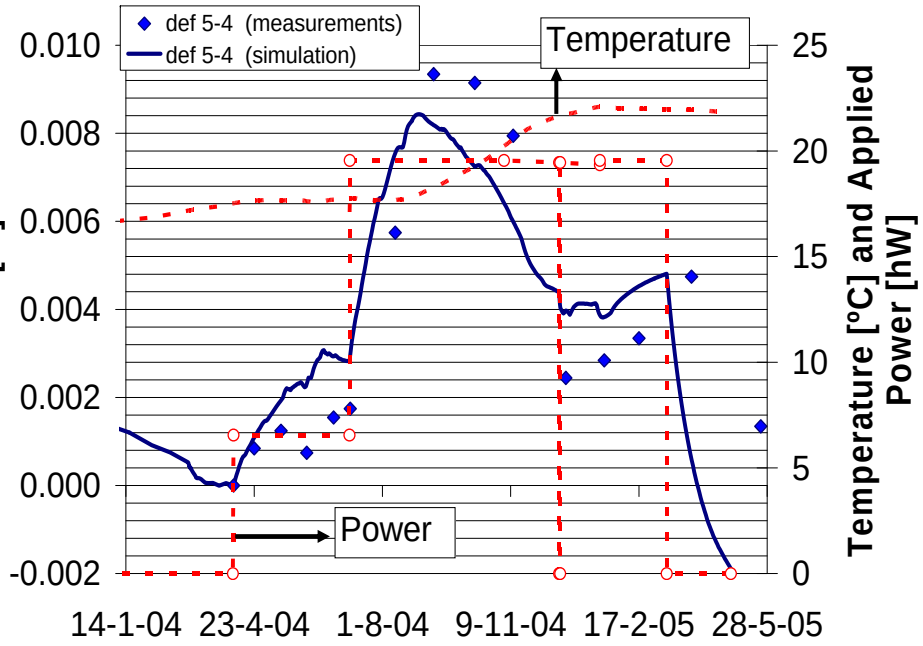
HE-D: deformation

Measured and simulated strain evolution in the HE-D experiment

Close to the heater



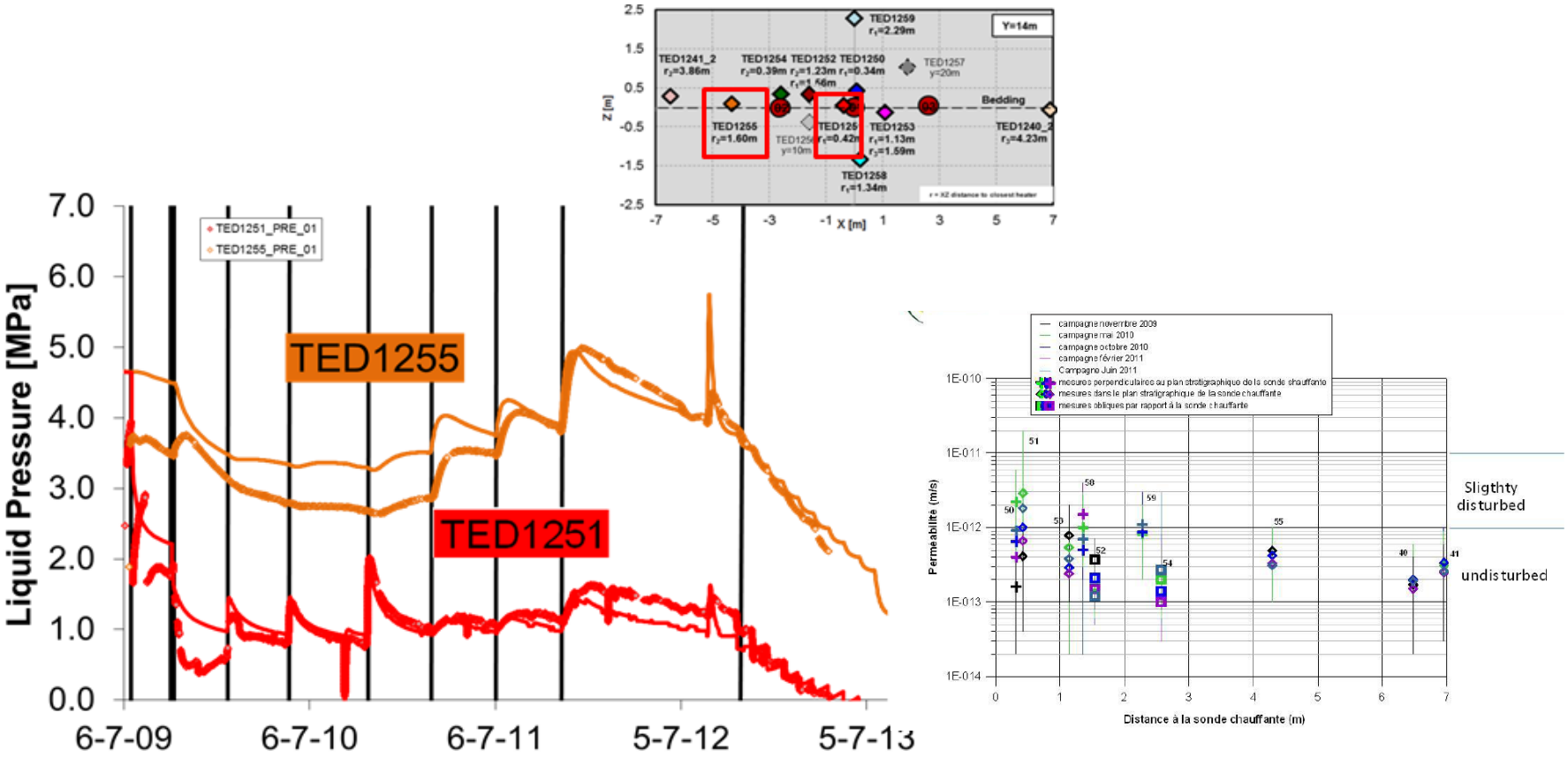
Close to the gallery



Positive is compression

nagra.

TED: pore water pressure and permeability



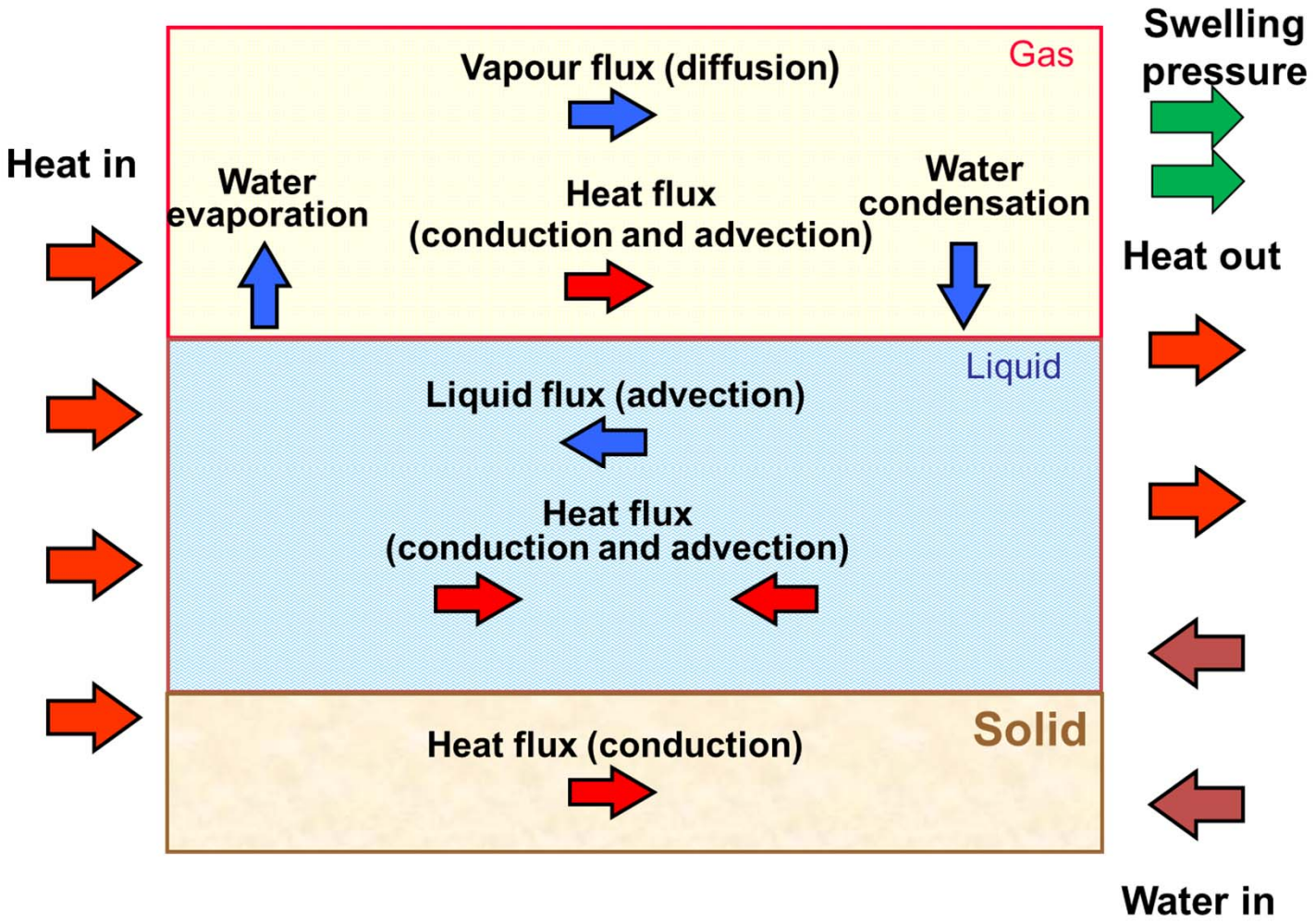
Evolution of pore water pressure during 4 years

Index

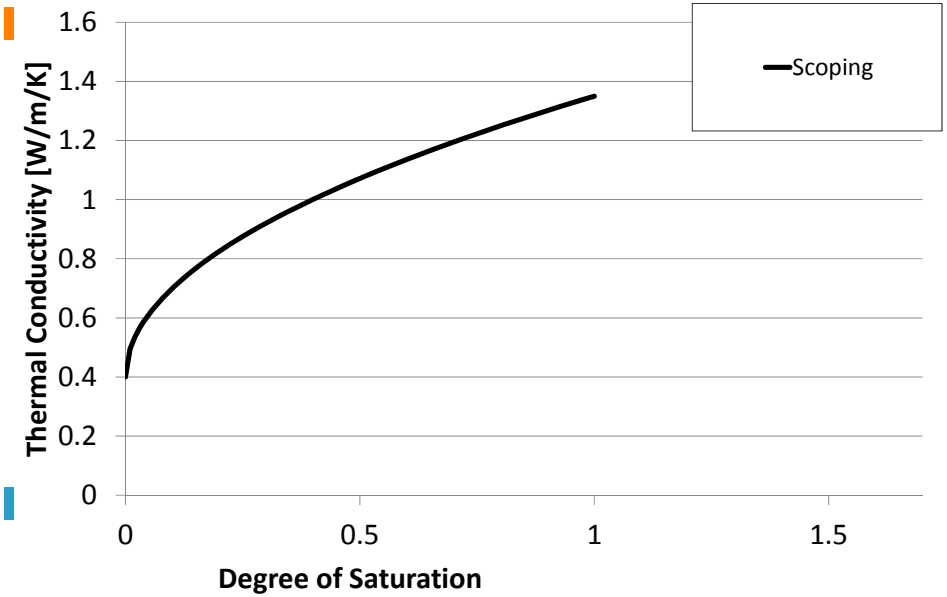
Note beforehand: many of the results presented herein come from my “previous” life. The measurements are mainly due to ANDRA and the TIMODAZ and PEBS projects.

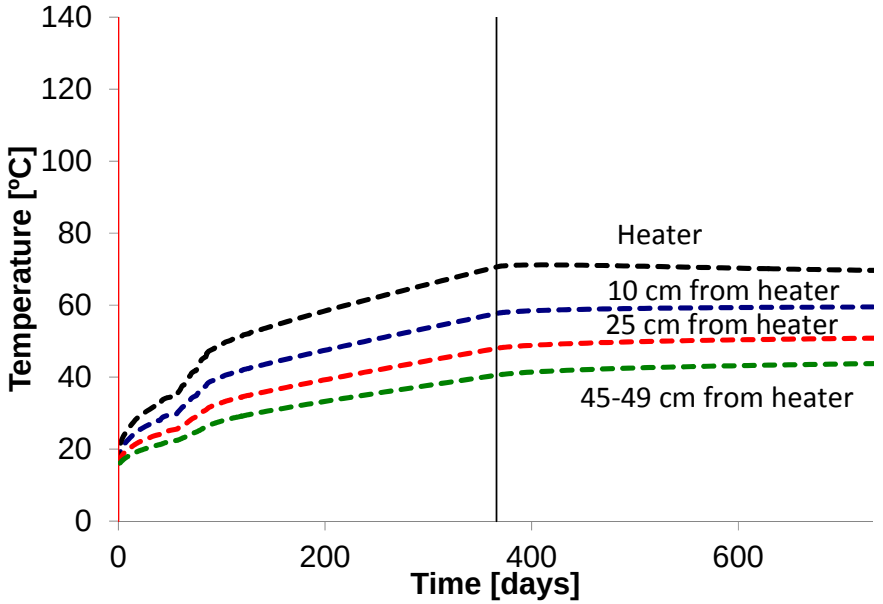
- Introduction
- Small scale experiments (HE-D, TER, TED and ATLAS)
  - Measurements
  - Modelling of the temperature field
  - Modelling of the pore water pressure field
- Larger and real scale experiments
  - HE-E
  - FE

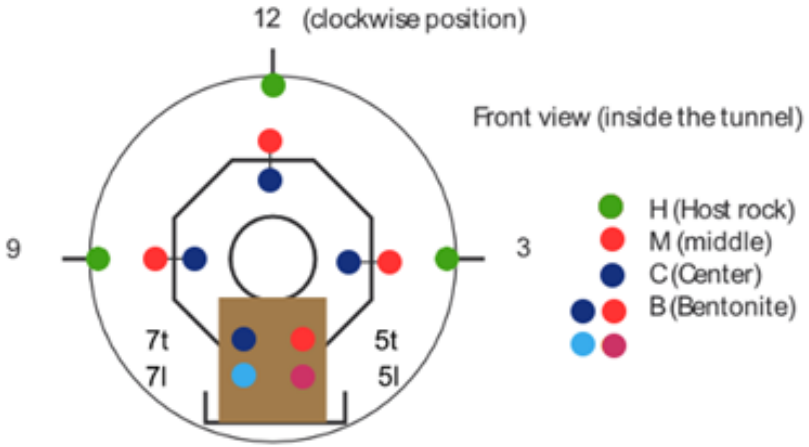
THM processes in the buffer



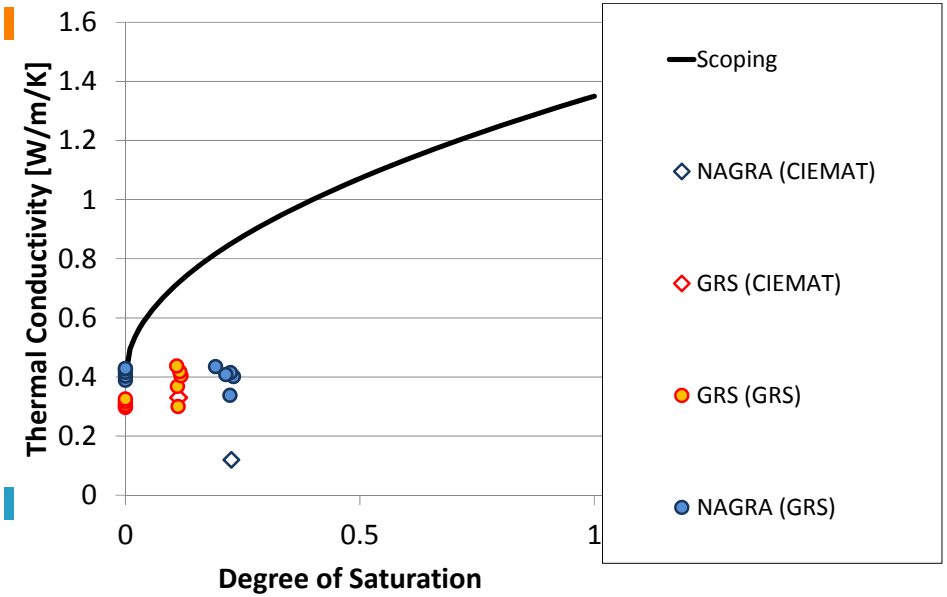
HE-E experiment: temperature

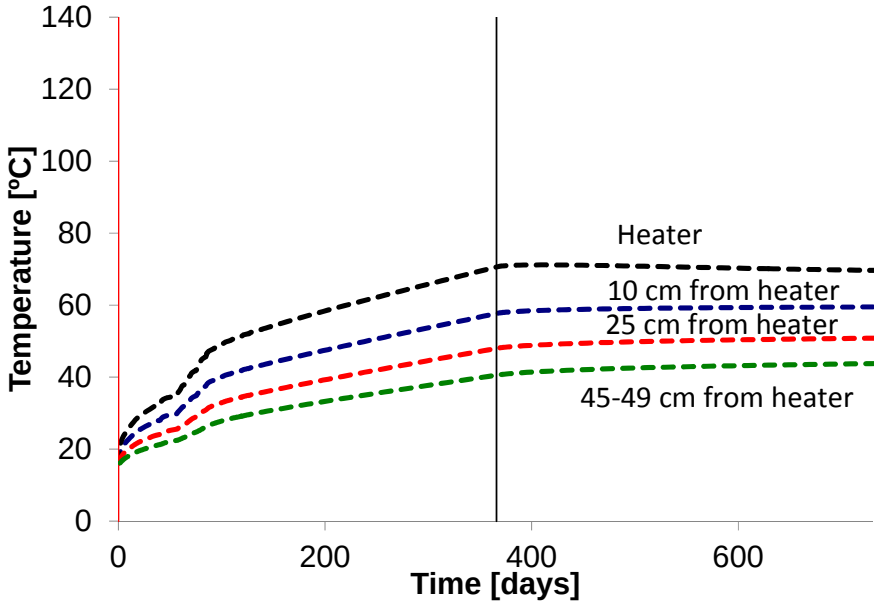


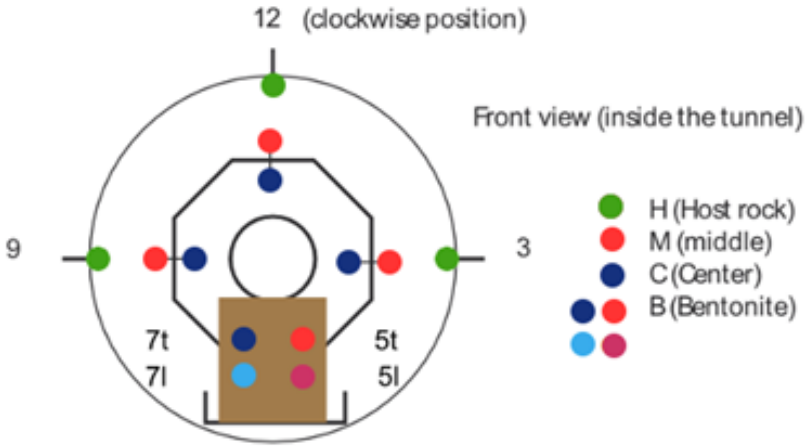




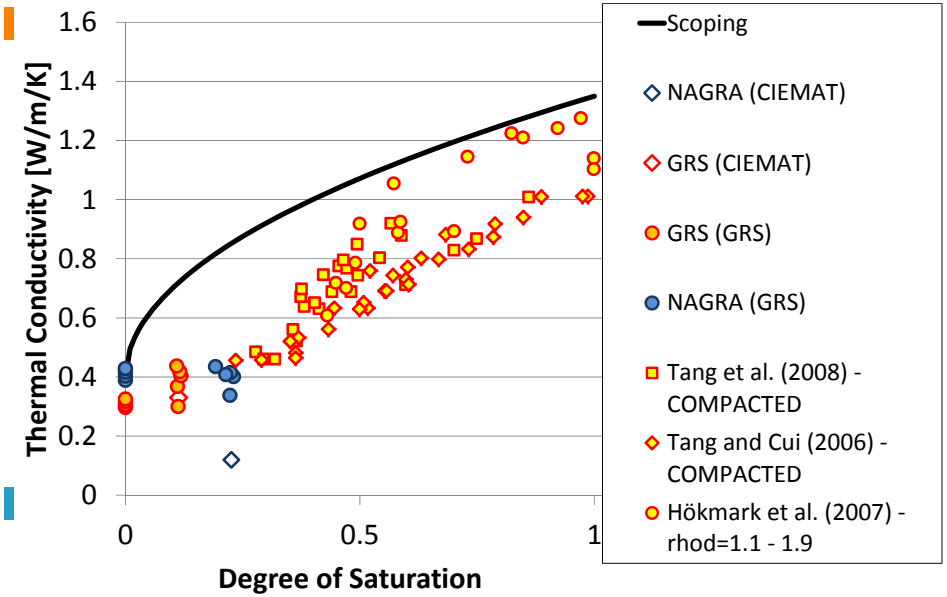
HE-E experiment: temperature

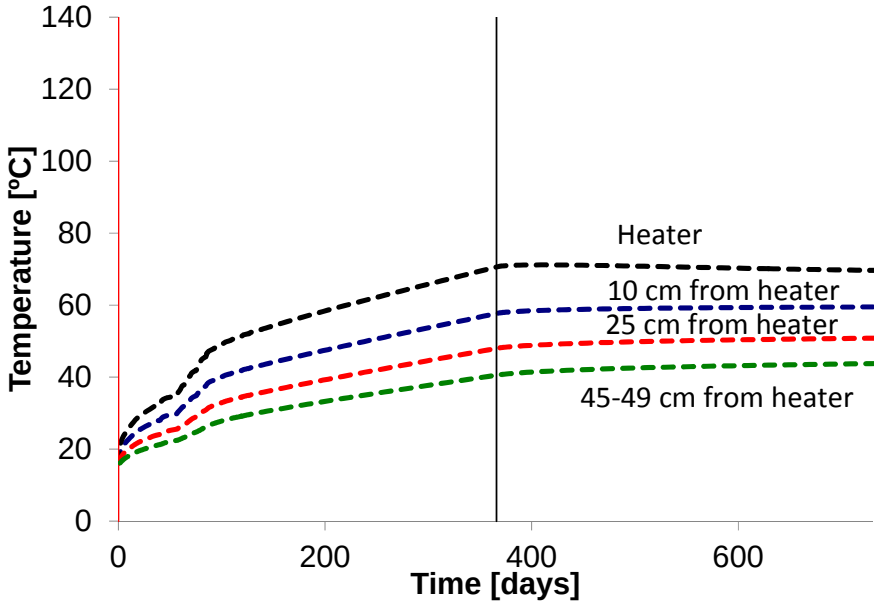


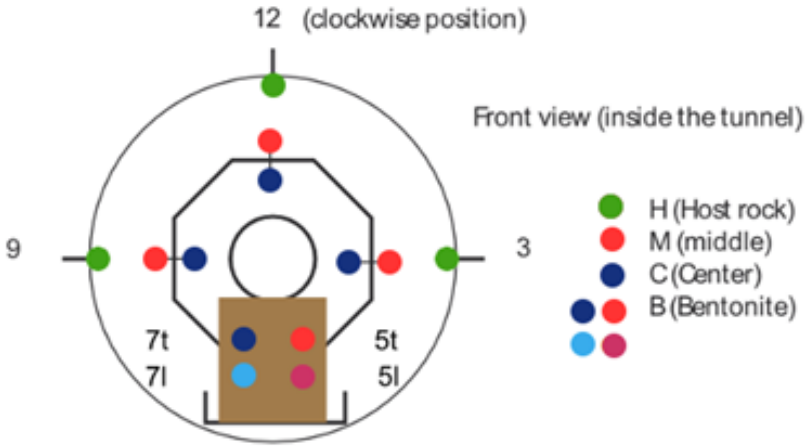




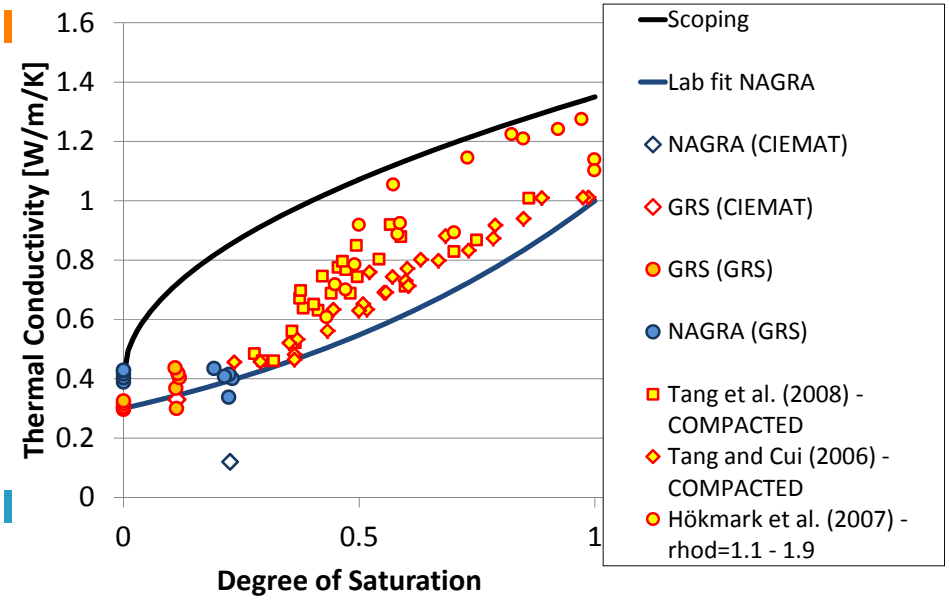
HE-E experiment: temperature

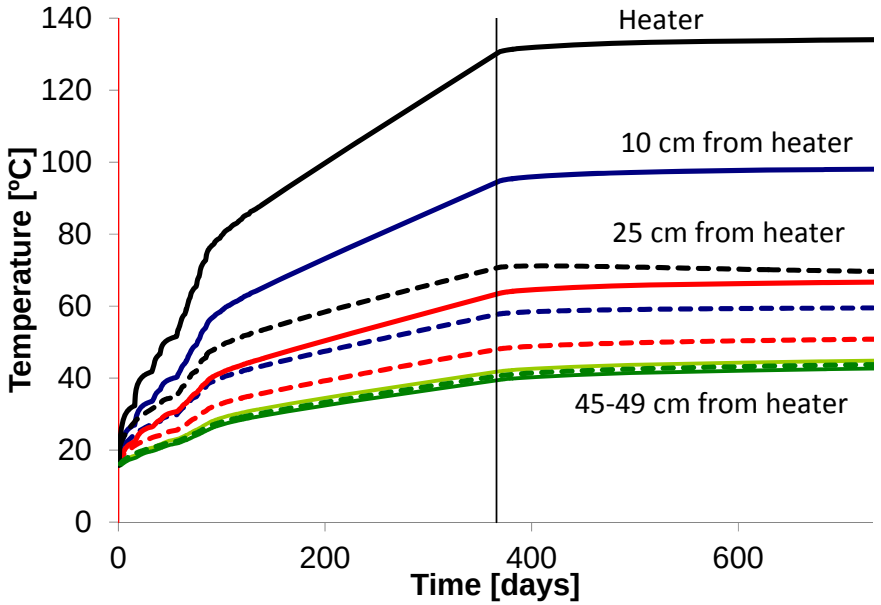


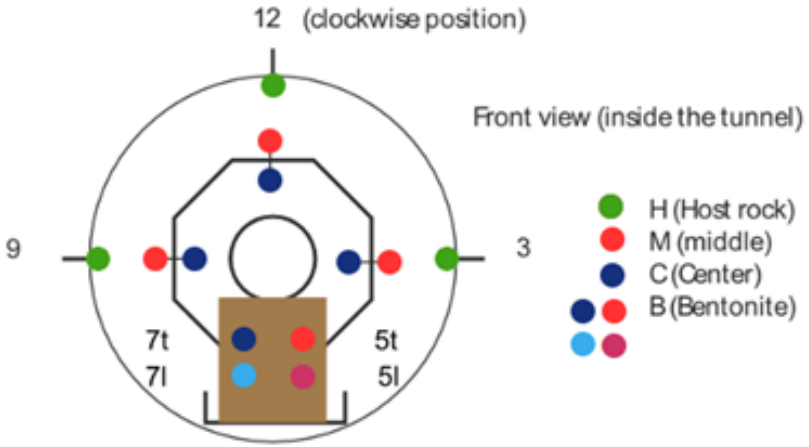




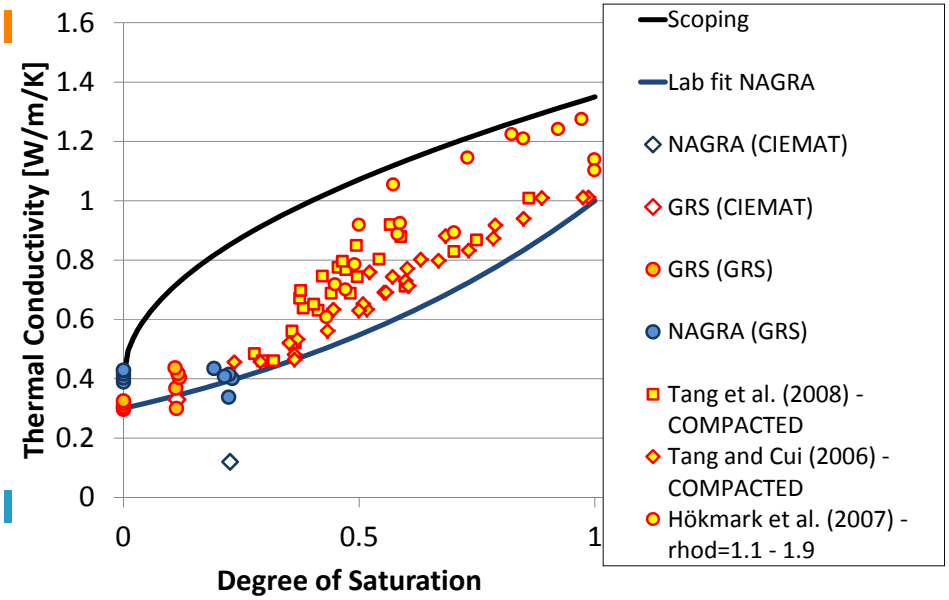
HE-E experiment: temperature

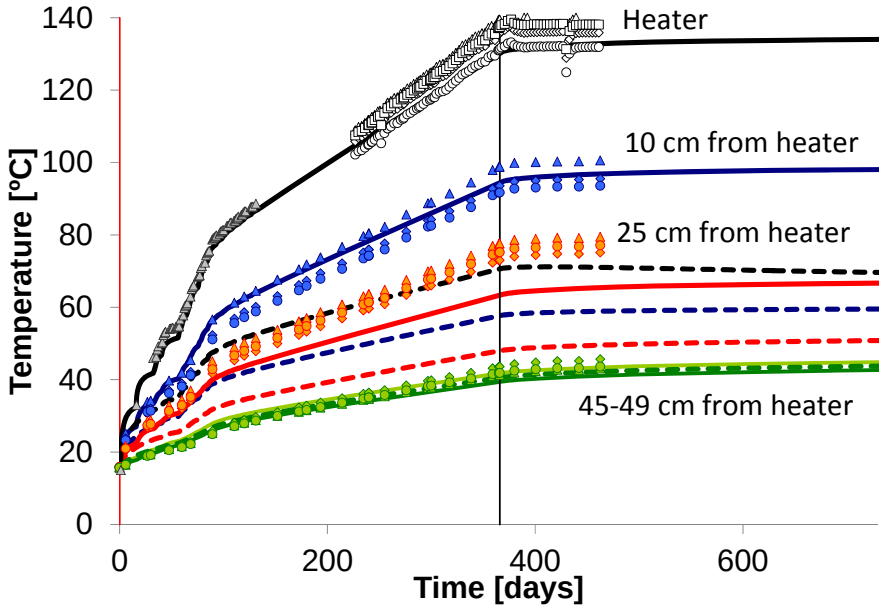


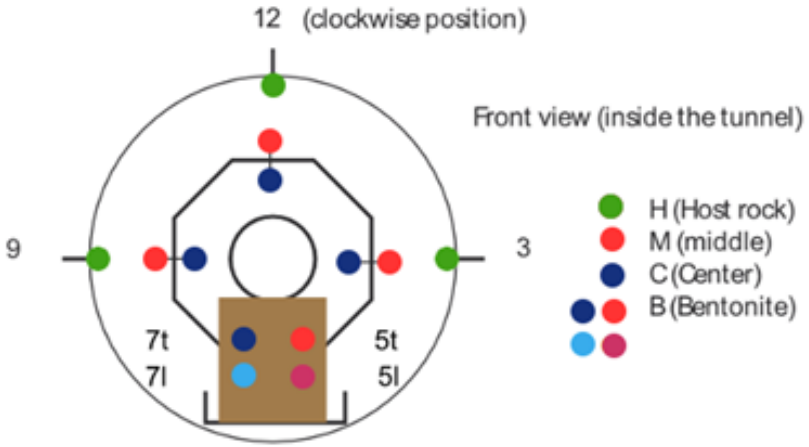




HE-E experiment: temperature

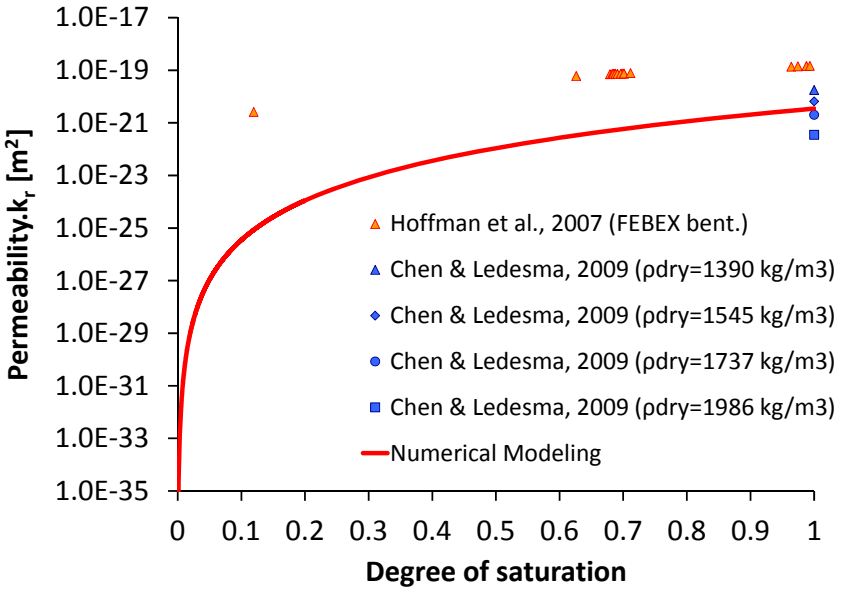


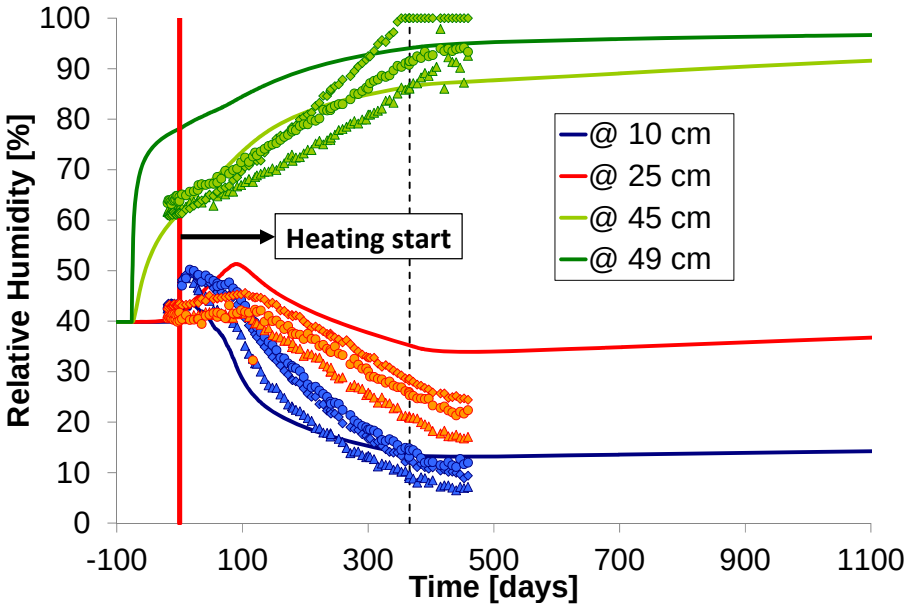


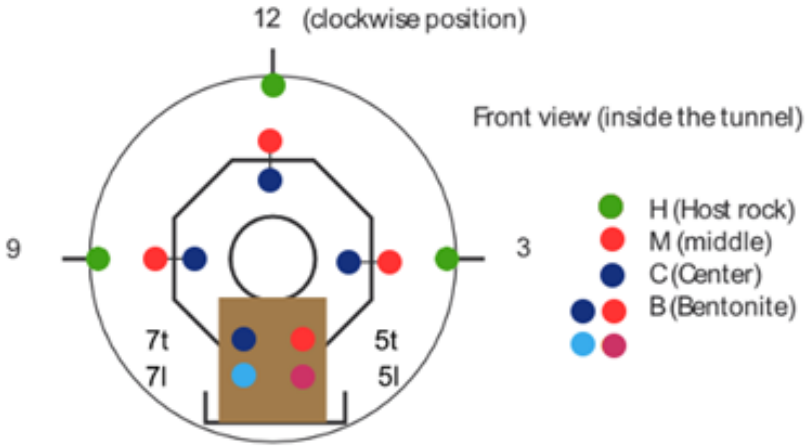


The saturation state…

HE-E experiment: relative humidity

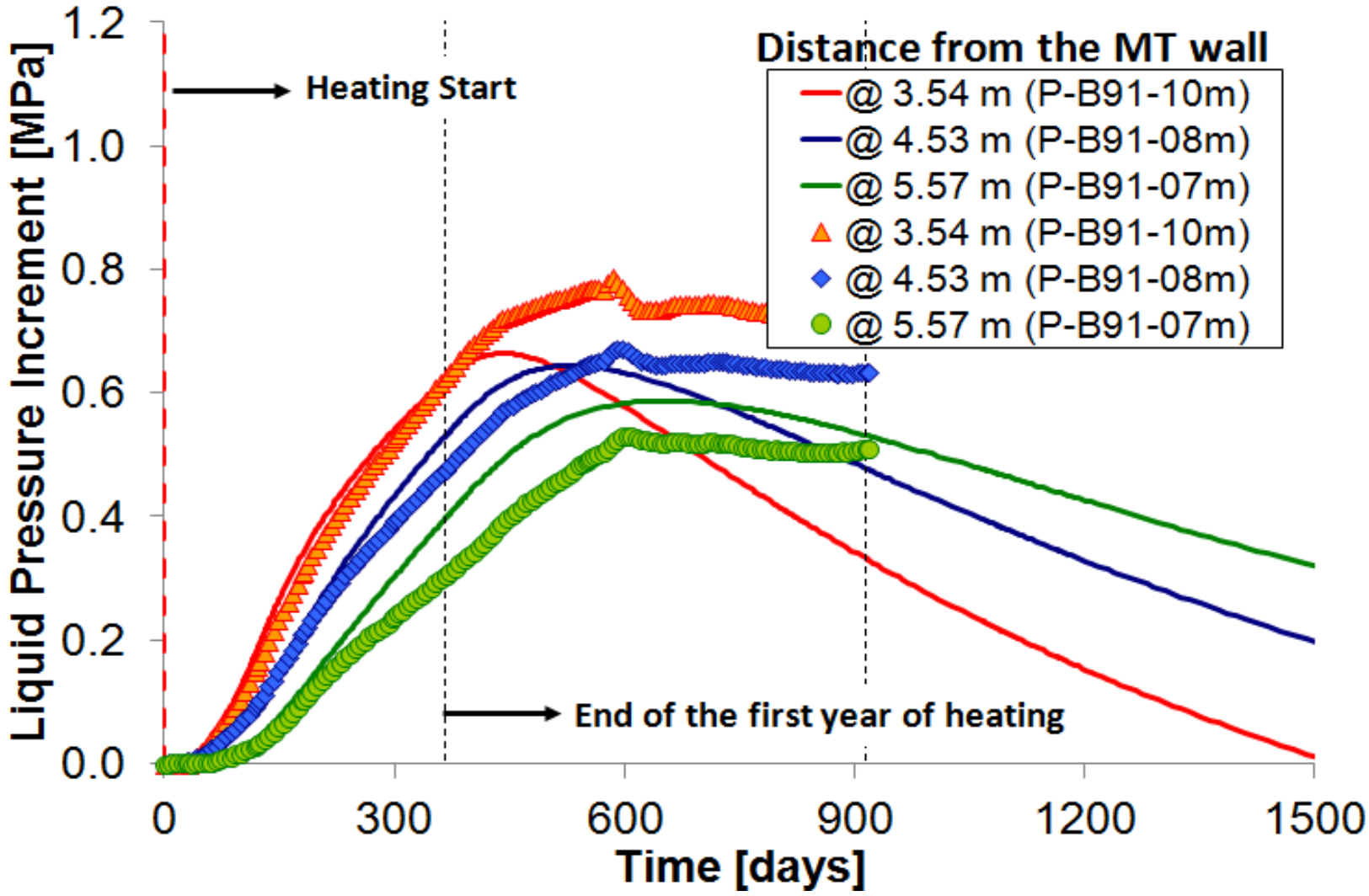






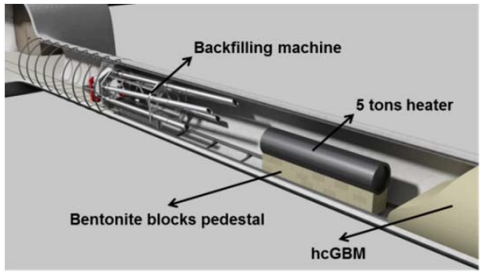
The saturation state depends i.a. on the permeability and vapour diffusion

HE-E experiment: pore water pressure

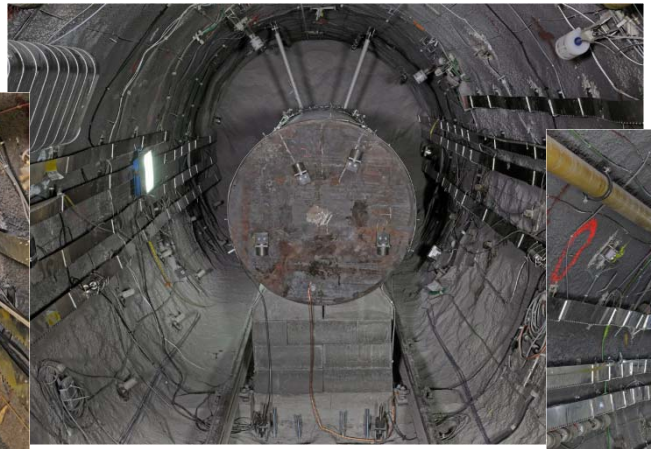


nagra.

FE experiment (photos by Comet)



3 heaters, 1500 sensors



400 tons of bentonite

5 tons, brought in horizontally with cm precision

nagra.

Commentaires finaux

- Au cours des 10 dernières années, de nombreux essais de chauffage ont eu lieu, permettant de:
  - Observer la **réponse thermo-hydro-mécanique de la roche** et de la caractériser
  - Mettre en avant le caractère **anisotrope** de la roche
- En général, les modèles arrivent à reproduire l'ensemble des données collectées (T, H & M, mais aussi toutes les données T), en conséquence:
  - Des modèles
  - De la précision de la mise en place de l'instrumentation

thank you
for your attention

nagra.