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Performance of the Opalinus Clay under thermal loading. Experimental results from Mont Terri rock laboratory (Switzerland)

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1 **Performance of the Opalinus Clay under thermal loading. Experimental results from**

2 **Mont Terri rock laboratory (Switzerland)**

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16

17 **Running title:** Performance of the Opalinus Clay under thermal loading

18 **Keywords:** temperature effects, in-situ tests, coupled THM phenomena, numerical analyses,

19 heating tests, pore pressures

20

1 **Abstract**

2 The paper presents an overview of the behaviour of Opalinus Clay under thermal loading as
3 observed in three in-situ heating tests performed in the Mont Terri rock laboratory: HE-B,
4 HE-D and HE-E. The three tests are summarily described; they encompass a broad range of
5 test layouts and experimental conditions. Afterwards, the following topics are examined:
6 determination of thermal conductivity, thermally-induced pore pressure generation and
7 thermally-induced mechanical effects. The mechanisms underlying pore pressure generation
8 and dissipation are discussed in detail and the relationship between rock damage and thermal
9 loading is examined using an additional in-situ test: SE-H. The paper concludes with an
10 evaluation of the various thermo-hydro-mechanical (THM) interactions identified in the
11 heating tests.

13 **1 Introduction**

14 Opalinus Clay has been selected in Switzerland as the preferred host rock for disposal of
15 high-level nuclear waste. In this context, the behaviour of Opalinus Clay is being intensively
16 investigated in the Mont Terri rock laboratory, an international project that has been ongoing
17 since 1996. Figure 1 shows the geological profile of the site. The exothermic nature of high-
18 level radioactive waste requires studies that target the performance of Opalinus Clay under
19 non-isothermal conditions so that the impact of heat on the geological barrier becomes well
20 understood.

21
22 The behaviour of an indurated mudstone, such as Opalinus Clay, under thermal loading has to
23 be considered in the framework of thermo-hydro-mechanical (THM) couplings as the various
24 THM phenomena interact. Thus, temperature variations will impact hydraulic behaviour due
25 to the generation of pore pressures and the variation of fluid viscosity and will affect the

1 mechanical behaviour through the development of thermally-induced strains. Hydraulic and
2 mechanical behaviour may interact with the thermal response through induced variations of
3 thermal conductivity. Heat convection is also a potential effects of hydraulic behaviour on the
4 temperature field although it is generally negligible in a low permeability medium. Figure 2
5 shows a scheme indicating the relationship between the most relevant thermal, hydraulic and
6 mechanical phenomena where the hydromechanical interactions have also been included. As
7 discussed later, not all the interactions have the same level of significance.

9 To examine the thermal behaviour of Opalinus Clay as well the associated coupled THM
10 effects, a number of thermal in-situ tests have been performed in the Mont Terri rock
11 laboratory: HE-B (initially called HE), HE-C, HE-D, HE-S, SE-H, HE-E and FE. Some of
12 them, such as HE-E and FE, are still ongoing. There have also been projects involving only
13 small-scale tests such as LT (Laboratory temperature testing) and TH-A (microscale THMC).
14 More details are given in Wileveau et al (2008).

16 This paper focuses on the behaviour of Opalinus Clay under thermal loading as observed in
17 three main heating field tests: HE-B, HE-D and HE-E that are summarily described first.
18 Afterwards, the results of those in-situ tests are reviewed in order to examine more closely the
19 behaviour of Opalinus Clay under thermal loading. Specifically, the following aspects are
20 discussed: thermal conductivity, pore pressure generation (thermo-hydraulic coupling) and
21 mechanical effects such as strain development and thermally-induced damage. The paper
22 concludes with a discussion on the coupled THM phenomena as observed in Opalinus Clay

2 The main in-situ heating tests

The three Mont Terri rock laboratory in-situ heating tests considered are: HE-B, HE-D and HE-E. They encompass a variety of features concerning the geometrical setting, presence and type of backfill, maximum temperature and heating duration. Table 1 contains the main characteristics of the tests whereas Figure 3 shows their location in the Mont Terri rock laboratory. At the Mont Terri rock laboratory, the overburden height varies between 250 m and 320 m. Opalinus Clay is intensively bedded; the closely-spaced bedding planes dip at an angle of approximately 45° at the laboratory location. All tests have been performed in the shaly facies of Opalinus Clay.

2.1 The HE-B experiment

The HE-B experiment involved placing a heater of 0.1 m diameter and 2.02 m long in a 300mm diameter vertical borehole. The borehole was 7.5m deep and was drilled in a niche excavated for this purpose. The heater was surrounded by a compacted clay barrier made up of ring-shaped Febex bentonite blocks with a dry density of 1.8 g/cm³. 19 boreholes were drilled in the niche floor to install sensors to measure temperature, relative humidity, total stresses, pore pressures, displacements and electrical resistivity. Devices to determine gas and water release were also installed in the boreholes. The layout of the main borehole containing the heater and the distribution of the monitoring boreholes in the niche are depicted in Figure 4.

Before heating was started, the barrier was hydrated artificially for 35 months using synthetic Pearson water (similar in chemical composition to the water present in the Opalinus Clay). Afterwards heating was applied during a 18th month period. Once a maximum temperature of

1 100°C was reached in the bentonite, heater power was adjusted in order to keep that
2 maximum temperature constant. The heating period of the experiment spanned from February
3 2002 to the end of August 2003. At the end of the heating period, the heater was switched off
4 and, after 1 month cooling period, the test was dismantled. Geotechnical, hydraulic and
5 seismic field tests were performed at the end of the test and a number of rock samples were
6 retrieved for testing in the laboratory. A full description of the test has been presented in
7 Göbel et al. (2007), only some representative results are shown here.

9 Figure 5 shows the distribution of temperatures of the rock (at the central section of the
10 heater) at different times of the heating test. It can be observed that, although a 100°C
11 temperature was applied by the heater, the maximum rock temperature only reached about
12 40°C and dropped rapidly with distance. This is the consequence of the layout of the test (a
13 single heater borehole) and the insulating nature of the bentonite barrier. In spite of the
14 modest increase in temperature, significant pore pressures develop in the Opalinus Clay (Fig.
15 6). A fast initial development of pore pressures followed by a more gradual dissipation can be
16 observed. The final sudden pore pressure drop is due to the cooling period that followed the
17 switching off of the heater. Higher temperatures in borehole BHE-19 (located at 0.65, from
18 the central borehole axis) give rise to higher pore pressures than those measured in borehole
19 BHE-20 located 2 meters away and subjected, therefore, to lower temperatures.

21 2.2 The HE-D experiment

23 To perform the in-situ heating test HE-D a niche was also excavated off Gallery 98 from
24 which a 30 cm diameter borehole (D0) was drilled horizontally up to a total length of 14 m. A
25 location was selected away from previous experiments in order to test intact rock properties.

1 In the section close to the end of the borehole, two heaters were installed. The heaters were
2 2m long and their separation was 0.8m, In this case there was no bentonite barrier and the
3 heaters were in direct contact with Opalinus Clay. To achieve a good contact with the rock,
4 the heaters were pressurized to 1 MPa. In addition, a number of auxiliary boreholes have been
5 constructed to install a variety of instruments for monitoring the test. Figure 7 shows a top
6 view of the test area. A horizontal test layout was chosen in order to have a largely uniform
7 lithology.

8
9 Temperatures were measured along two boreholes drilled (D1 and D2) from the niche HE-D.
10 However, perhaps the most relevant observations were those combining measurements of
11 temperatures and pore pressures at the same point in order to relate directly the two variables.
12 This was achieved in borehole D3 (drilled parallel to the heater borehole) and in a series of
13 small diameter boreholes (D7 to D17) drilled from the MI niche. The pore pressure
14 measurements of sensors located below the main borehole were quite successful but the pore
15 pressure probes located above the main borehole exhibited a rather slow response attributed to
16 difficulties encountered in de-airing the sensor area. Finally, sliding micrometer tubing was
17 installed in boreholes D4 and D5 to measure incremental deformations at 1 m intervals.
18 Special care was taken to ensure accuracy in the direction and length of the instrumentation
19 boreholes to guarantee the correct location of the sensors. All instruments were in place
20 before the drilling of the main borehole containing the heaters. In this way hydro-mechanical
21 effects during excavation could also be recorded. Full information on the test is given in
22 Wileveau (2005).

23
24 Approximately one month after installation and pressurization, the heaters were switched on
25 with a total power of 650 W (325 W per heater). The heaters were then left under constant

1 power during 90 days. Afterwards the power was increased threefold, to 1950 W (975W per
2 heater) and maintained at that level for 248 days more. The heating period lasted from March
3 2004 to February 2005. At the end of the second heating stage, the heaters were switched off
4 and the clay was allowed to cool down. Temperatures, pore pressures and deformations were
5 measured throughout. Examples of the observations obtained are shown in Figures 8 and 9 in
6 terms of evolution of temperatures and pore pressures at different distances from the heaters.
7 The pattern of results is similar to that of the HE-B experiment but the increase of pore
8 pressure is now significantly higher as a result of the different test design.

2.3 The HE-E experiment

12 The HE-E experiment has been installed in a section of the 1.3 m diameter and 50 m long
13 microtunnel excavated in 1999 using the raised-boring technique. The same section of the
14 microtunnel had been used previously for a ventilation test (VE). The layout of the
15 experiment is shown in Figure 10. Two 4 m-long heaters have been used separated by a plug.
16 Heater 1 is surrounded by an engineered barrier composed of granular MX-80 bentonite made
17 up of pellets with a mean diameter 1 mm approximately and sits on a bed of MX-80
18 compacted blocks. The dry bulk density of the granular bentonite as placed is 1.46 g/cm^3 and
19 the dry density of the blocks is $1,806 \text{ g/cm}^3$. The arrangement of Heater 2 is the same except
20 that the granular material used in the barrier is a mixture of sand and MX-80 bentonite. The
21 resulting dry density of the granular sand/pellet mixture is 1.50 g/cm^3 . No artificial hydration
22 is used for saturating the engineered barrier, so water uptake by the bentonite will be very
23 limited due to the low permeability of the Opalinus Clay.

1 Extensive instrumentation was used to monitor the progress of the test in the following
2 locations: i) the heater surface where the temperature is controlled, ii) the engineered barrier
3 and the interface with the Opalinus Clay (temperature and relative humidity), iii) the Opalinus
4 Clay close to the microtunnel using the sensors from the VE test (temperature, humidity,
5 water pressure and displacement), and iv) the Opalinus Clay at distances ranging from 2 to 6
6 meters from the microtunnel (pore pressures). This test is fully described in Gaus et al. (2014).

7
8 The heating stage started at the end of June 2011 and it is still ongoing at present as this
9 experiment is intended as a long-term test. Heating power was gradually raised over a period
10 of one year approximately until reaching a maximum temperature on the heater surfaces of
11 140°C. From that moment on, heater power has been adjusted to keep this control temperature
12 constant. Figure 11 shows the recorded evolution of heater power. The observed difference
13 between the two heaters is due to the different thermal conductivities of the two materials
14 used for the engineered barriers. The evolution of the temperatures in Opalinus Clay close to
15 heater 1 is presented in Figure 12. It can be seen that close to the tunnel/barrier interface the
16 temperature has reached 90 °C but it drops sharply as the distance to the tunnel increases.
17 Figure 13 shows the evolution of thermally-induced pore pressures at distances ranging from
18 3.5 to 5.5 meters. It can be observed that at the end of the period considered, pore pressure
19 reduction is not apparent yet.

20 .
21 The HE-E test has a number of novel features such as a temperature higher than 100°C,
22 natural hydration and granular bentonite used in the engineered barrier, enlarging in this way
23 the range of conditions under which the response of Opalinus Clay has been observed. In spite
24 of the differences between the three tests, the basic characteristics of the response are quite
25 similar so that they can be used to derive some general observations on the non-isothermal

behaviour of Opalinus Clay, as described in the following sections. The main effort is placed in the analysis of the HE-D test as it is not affected by the presence of an engineered barrier and the behaviour of the Opalinus Clay can be observed in a more direct manner.

3 Thermal conductivity

The low permeability of Opalinus Clay ensures that the heat transport by advection is negligible; conduction is the only relevant heat transfer mechanism. Therefore, the thermal field is basically controlled by the value of thermal conductivity, λ , the coefficient that links, in Fourier's law, the conductive flux, \mathbf{i}_c , to the gradient of temperature, T :

$$\mathbf{i}_c = \lambda \nabla T \quad (1)$$

Although tests HE-B and HE-E have been analysed assuming an isotropic thermal conductivity (Göbel et al 2007; Gaus et al. 2014), it is well established that thermal conductivity of Opalinus Clay is anisotropic (Bossart 2008) exhibiting different values in the directions normal and parallel to bedding. With the coordinates aligned adequately, equation (1) becomes:

$$\mathbf{i}_c = \begin{bmatrix} \lambda_{par} & 0 & 0 \\ 0 & \lambda_{par} & 0 \\ 0 & 0 & \lambda_{per} \end{bmatrix} \cdot \nabla T \quad (2)$$

where λ_{par} and λ_{per} are the thermal conductivity values in the bedding plane and in the perpendicular direction, respectively.

If a sufficient number of temperature measurements are available, it is in principle possible to estimate the thermal conductivity values from a backanalysis of an in-situ heating test. Because the thermal problem is largely independent of the hydromechanical one, performing

1 a purely thermal analysis suffices. However, as demonstrated by Garitte et al. (2014), there
2 are pitfalls if a conventional backanalysis is performed in which a least square criterion is
3 applied blindly to the ensemble of all the results giving the same weight to all of them. Such
4 conventional analysis can easily provide biased results depending on the sequence of
5 observation times considered as well as on the location of the sensors.

6
7 In this context, the analysis of a synthetic case consisting of a heat point source has provided
8 key insights. This problem has an analytical solution (Booker and Savidou 1985) that can be
9 applied to anisotropic thermal conductivity conditions using an equivalent thermal
10 conductivity (Carslaw and Jaeger 1946):

$$\lambda_0 = \sqrt[3]{\lambda_{par} \cdot \lambda_{par} \cdot \lambda_{per}} \quad (3)$$

11
12 Figure 14 shows the thermal conductivity parameter pairs that provide a good agreement (i.e.
13 an error of less than 2%) with the analytical solution. It can be noted that the combination of
14 the thermal parameters vary depending on the time at which the backanalysis is performed.
15 The Figure clearly indicates that short term and long term observations provide different
16 information on the combinations of λ_{par} and λ_{per} that provide a good representation of the
17 results. Therefore, to identify independently the two thermal conductivity values, it is
18 essential to combine the short term and the long term observations in an appropriate manner.
19 Building on those observations, the following procedure was recommended (Garitte et al.
20 2014):

21
22 i) 3D analyses of the experiment considered are performed using different thermal
23 conductivity pairs covering a wide range. 3D analyses are required to take into account
24 anisotropy.

1 ii) Values of thermal conductivity minimizing the difference between observations and
2 calculations are obtained for each individual sensor and for each heating phase. The
3 determination of the pair of thermal conductivity values is performed from the combination of
4 short term and long term data. Outliers are removed from the backanalysis.

5
6 iii) An overall value of thermal conductivities is obtained from the average of all the sensors.
7 If there are significantly different numbers of sensors aligned parallel and perpendicular to the
8 bedding planes, the average of each orientation will be computed first and a final overall
9 value will be obtained from the average of the sensors at the two different orientations.

10
11 The analyses for the synthetic case also allowed identifying the effects of experimental
12 uncertainties in sensor location, power input, temperature measurements and specific heat.
13 For instance, if there is a significant difference between the thermal conductivities computed
14 from sensors parallel and perpendicular to bedding planes, it is an indication of uncertainty in
15 the heating power that may then be adjusted accordingly.

16
17 The procedure just outlined has been applied to the observations of the HE-D test. The results
18 are shown in Figure 15 (Garitte et al. 2014). It can be noted that the parallel sensors and the
19 perpendicular sensors tend to indicate different thermal conductivity pairs. Some power loss
20 was assumed as a possible explanation for this kind of pattern and a second analysis was
21 accordingly performed. Diamond dots indicate the analysis in which no power loss was
22 applied and circle dots indicate the best-fitting thermal conductivity pairs determined in an
23 analysis considering a power loss of 5%. Due to the differences between the two sensor
24 groups and to the fact that more perpendicular sensors were available in the HE-D experiment,
25 the averages of the perpendicular sensors and of the parallel sensors are done first and then

1 the final average is computed. In this way, the best estimates for the thermal conductivity are:
 2 $\lambda_{\text{par}}= 2.15 \text{ W/m}^\circ\text{K}$ and $\lambda_{\text{per}}= 1.2 \text{ W/m}^\circ\text{K}$, an anisotropy ratio of 1.8. Those values are
 3 remarkably close to those obtained in the laboratory (Bossart 2008). It is also interesting that
 4 the backcalculated values for all sensors tend to cluster close to a value of equivalent thermal
 5 conductivity of about $1.8 \text{ W/m}^\circ\text{K}$.

7 **4. Thermally-induced pore pressure generation**

8 In Opalinus Clay, the main hydraulic phenomenon associated with thermal effects is the
 9 generation of pore pressure due to changes of temperature. When Opalinus Clay (and other
 10 argillaceous rocks) is subjected to a temperature increase, the pore pressure will also increase
 11 due to the fact that the thermal expansion of the water is larger than that of the porous
 12 skeleton itself. The low permeability of Opalinus Clay ensures that the resulting excess pore
 13 pressure does not dissipate rapidly. As a matter of fact, quite a number of interactions underlie
 14 this pore pressure generation phenomenon; they are best viewed by considering the water
 15 mass balance equation:

$$37 \quad n \frac{D_s \rho_w}{Dt} + \frac{\rho_w}{\rho_s} \cdot (1-n) \cdot \frac{D_s \rho_s}{Dt} + \rho_w \cdot \nabla \cdot \frac{d\mathbf{u}}{dt} + \nabla \cdot (\rho_w \cdot q_l) = 0 \quad (4)$$

16 where n is the porosity, ρ_w and ρ_s are the water and solid densities respectively, t is time, \mathbf{u} are
 17 displacements and q_l is Darcy's liquid velocity. D_s denotes material derivative.

18
 19 Equation (4) can be further developed taking into account the variation of the liquid and solid
 20 densities that, with some simplifications, are assumed to be given by:

$$54 \quad \rho_w = \rho_{w0} \cdot \exp \left[\beta_w (p_l - p_{l0}) + b_w (T - T_{ref}) \right] \quad (5)$$

$$57 \quad \rho_s = \rho_{s0} \cdot \exp \left[\beta_s (p_s - p_{s0}) + 3 \cdot b_s \cdot (T - T_{ref}) \right] \quad (6)$$

1 where β_w and β_s are the water and solid compressibilities, respectively, and b_w and b_s are the
 2 volumetric and linear thermal expansion coefficient for water and the solid phase, respectively.
 3 p_l is the liquid pressure, p_s is the solid pressure, and T is temperature.

4
 5 Then equation (4) becomes:

$$\left[n \cdot b_w + (1-n) \cdot 3 \cdot b_s \right] \cdot \frac{D_s T}{Dt} + n \cdot \beta_w \cdot \frac{D_s p_l}{Dt} + (1-n) \cdot \beta_s \cdot \frac{D_s p_s}{Dt} + \nabla \cdot \frac{d\mathbf{u}}{dt} + \frac{\nabla \cdot (\rho_w \cdot q_l)}{\rho_w} = 0 \quad (7)$$

6
 7 The generation and dissipation of pore pressure in the clay due to a temperature change
 8 can be more readily understood examining equation (7). The first term arises from the
 9 differential thermal expansion of solid and liquid phases. The second and third terms are the
 10 volume changes of water and solid phase associated with a pore pressure and solid pressure
 11 change; the fourth term is the volume change of the material skeleton (that includes
 12 contributions from stresses, pore pressures and temperature) and the fifth term corresponds to
 13 the flow of water in or out of the clay element considered. The interplay of all those
 14 phenomena results in the generation of pore pressure and its evolution with time.

15
 16 Interesting insights can be obtained examining a typical evolution of temperature and pore
 17 pressure as presented in Figure 16. It was recorded in borehole D3 (Fig. 7) with the sensors
 18 located 1.1 m away from the axis of the heater in the direction of the bedding planes. It can be
 19 observed that pore pressures react immediately to heating, exhibiting a very strong response.
 20 Increments of 2.25 MPa are measured at this particular location; this is a magnitude similar to
 21 the estimated minor principal stress in the area. It is also interesting to note that the evolutions
 22 of temperature and pore pressures do not coincide. Pore pressure reaches a maximum at a
 23 particular time and then it decreases in spite of the fact that temperature continues to rise. This
 24 is the result of the interplay between the generation of pore pressures due to thermal action

1 and the dissipation of pore pressures due to consolidation. At this particular location,
2 dissipation by liquid-flow overcomes the temperature increase effects in the later stages of the
3 experiment.

4
5 A numerical three-dimensional coupled THM analysis was performed so that the anisotropy
6 of the material (thermal conductivity and stiffness) and of the in-situ stress system could be
7 incorporated in the calculations. Due to the special characteristics of Opalinus Clay, a
8 constitutive model that tries to account for the fact that the microstructure of the material is a
9 combination of clay matrix and cementing bonds have been used (Vaunat and Gens 2003a,
10 2003b). A full description of the numerical modelling of the in-situ test as well as the
11 parameters used is presented in Gens et al. (2007).

12
13 Figure 17 presents, for a number of points of the clay, the comparison between the results of
14 the 3D analysis and the observations in terms of pore pressure increases. The results of two
15 companion axisymmetric analyses have also been added for reference. The maximum pore
16 pressure increase is largely well captured and the evolution of pore pressure is also well
17 reproduced with the exception of borehole D17 located further away from the heaters. The
18 pore pressure rise obtained in the computations in the first heating stage is faster than the
19 observed one. This could be due to a slow response of the pore pressure sensors; it can be
20 noted that in the second stage, when the piezometers are likely to be fully saturated, the
21 observed and computed rate of pore pressure increase appear to be the same.

22
23 In Figure 17, it can also be noted that the time at which the maximum pore pressure increase
24 is calculated becomes larger as the distance to the main borehole increases. This is a
25 consequence of the combined effect of the movement of the temperature rise outwards and of

1 pore pressure dissipation from the inner zones. Computed pore pressure distributions on a
2 section perpendicular to the main borehole and located between the two heaters are plotted for
3 various times in Figure 18. They correspond to two perpendicular directions; one along the
4 bedding plane direction and the other one along a direction normal to the bedding. The
5 differences that can be observed between the distributions in the two directions are not caused
6 by hydraulic effects (permeability was assumed isotropic) but they arise from the different
7 temperature rise brought about by the anisotropy of thermal conductivity.

8
9 The anisotropy and the evolution of pore pressures can also be observed in the contours of
10 equal pore pressure presented in Figure 19 where the displacement with time of the maximum
11 of pore pressure away from the main borehole can be observed. The Figure also shows that
12 the cooling associated with the switching off of the heaters produces a reduction in pore
13 pressure, the counterpart of the pore pressure rise during heating.

14
15 Availability of a successfully validated numerical model allows the performance of a
16 series of sensitivity analyses to explore the potential effects of a number of parameters and, in
17 this way, improve the understanding of the mechanisms causing the thermally-induced
18 generation of pore-water pressures. The values of Young's modulus, Biot coefficient, solid
19 compressibility, thermal expansion coefficients and thermal conductivity have been varied
20 over a rather wide range. In all cases, the effect on the generated pore pressures was found to
21 be either modest or negligible (Gens et al. 2007).

22
23 The effect of intrinsic water permeability is however very significant. This is not surprising
24 because the magnitude of the pore pressure generated results from a competition between the
25 effects of differential thermal expansion of liquid and clay skeleton and the dissipation of pore

1 pressures, the rate of which is controlled basically by the value of rock permeability. The
2 results of sensitivity analyses with values of intrinsic permeability varying in the plausible
3 range (for Opalinus Clay) of 10^{-19} m^2 to 10^{-20} m^2 (the reference value is $5 \times 10^{-20} \text{ m}^2$) are
4 shown in Figure 20a. The effect on generated pore pressures is large. Because of the weight of
5 this parameter in the global behaviour of the test, two additional analyses have been
6 performed using intrinsic permeabilities of 10^{-23} m^2 and 10^{-16} m^2 to correspond to practically
7 undrained and practically drained conditions. As Figure 20b shows, in the very low
8 permeability case there is an extremely large increase of pore pressures that tracks closely the
9 temperature evolution; dissipation is practically negligible and undrained conditions
10 predominate. In contrast, Figure 20b also shows that in the very large permeability case no
11 pore pressure generation is observed since pore pressure dissipation dominates throughout. It
12 should be noted that although Opalinus Clay is a low permeability material, pore pressure
13 dissipation plays a critical role with respect to the magnitude of the pore pressures generated
14 by thermal action. If there were no dissipation, pore pressures would reach values above 12
15 MPa in the rock close to the heater.

17 **5. Thermally-induced mechanical effects**

18 Mechanical effects result from the joint action of temperature changes and pore pressure
19 generation and dissipation. They can be perceived from the measurements of relative
20 displacements in boreholes D4 and D5 performed using a sliding micrometer (Fig. 7).
21 Borehole D5 was drilled at a direction approximately normal to the main borehole containing
22 the heaters; the deformations measured at various times are plotted in Figure 21. It can be
23 observed that in the region around the heaters, extension deformations occur, but they become
24 compressive strains at locations further away from the heater. The volume increase of the clay
25 close to the heater, driven by thermal expansion, produces compression in the outer zones. The

1 evolution of strains of some selected intervals of borehole D5 is shown in Figure 22 together
2 with the computed results from the analyses. A thermal expansion coefficient of $1.4 \times 10^{-5} \text{ K}^{-1}$
3 has been adopted, following Auvray (2004). A first observation is the very small magnitude
4 of the strains (and hence displacements) measured and computed, consistent with the high
5 stiffness and modest thermal expansion exhibited by Opalinus Clay.

6
7 In borehole intervals close to the heater (e.g. intervals 6-7, 7-8 and 8-9 of borehole D-5)
8 dilatant strains are observed in response of the temperature increase; the two heating stages
9 can be easily recognized. In contrast, in borehole intervals away from the heater (e.g. intervals
10 11-12 and 12-13), compressive strains are measured in the initial stages due to the expansion
11 of the inner regions of the test. As the temperature increase field spreads out with time, the
12 rock expands and dilatant strains are observed and computed. In spite of some scatter of the
13 observations (due to the small magnitudes being measured), the numerical analyses capture
14 satisfactorily the main patterns of behaviour.

15
16 Unfortunately no direct observations of damage in terms of permeability variations were
17 obtained in test HE-D. So, the potential effect of heating on rock damage could not be
18 assessed. However, another in-situ heating test, SE-H, was subsequently performed as part of
19 the TIMODAZ project (Li et al. 2011). Heating was applied by circulating water at a high
20 temperature through a packer-isolated section of a 76mm diameter borehole installed in the
21 shaly facies of Opalinus Clay. A number of hydraulic tests were performed in an adjacent
22 borehole interval. It was found that after a temperature increase to about 65°C, intrinsic
23 permeability reduced by a factor of 4. So no adverse effects in terms of rock damage appear to
24 result from an increase of temperature, rather the opposite.

1 **6. Concluding remarks**

2 The understanding of the behaviour of Opalinus Clay under thermal loading has been much
3 advanced by the performance and study of a number of in-situ heating tests: HE-B, HE-D and
4 HE-E. Those tests cover a wide range of test layouts and conditions. In spite of this, the
5 observed behaviour of Opalinus clay is quite similar in the three cases. Although the
6 temperatures applied by the heaters are rather high, the temperature increases in the Opalinus
7 Clay have been generally moderate because of the rapid thermal attenuation with distance and
8 of the isolating nature of the engineered barriers in tests HE-B and HE-E. In spite of those
9 modest increases, the generation of pore pressures has been very significant in all cases. The
10 mechanism underlying the generation of pore pressures is well understood; it arises from the
11 combination of the effects of differential rock/water thermal dilation and of pore pressure
12 dissipation, controlled by rock permeability. There is less information on thermal effects on
13 mechanical variables; strains measured in the HE-D test, however, turn out to be quite small.
14 Hydraulic measurements carried out in a different test, SE-H, suggest that heating might be
15 beneficial with respect to rock damage as the intrinsic permeability reduced significantly after
16 an increase of temperature.

17
18 The HE-D test has been analysed in more detail because it involves no engineered barrier, so
19 the behaviour of Opalinus Clay under thermal loading can be examined more directly. From
20 those analyses, it is possible to assess the various THM phenomena involved and evaluate
21 their relative importance (Gens 2010):

- 22
23 – the strongest coupling corresponds to the effects of the thermal field on hydraulic and
24 mechanical behaviour. Pore pressure increases are caused by temperature rises

1 whereas thermal expansion is the most important source of rock deformation and
2 displacements. Deformations and displacements are however small.

3 – noticeable but more modest effects result from the coupling of hydraulic phenomena
4 to mechanical behaviour. The dissipation of pore pressures induces additional
5 displacements and strains that, due to the high Opalinus Clay stiffness, are smaller
6 than thermally-induced deformations.

7 – in principle, mechanical damage could impact the hydraulic observations if a zone of
8 higher permeability develops due to material damage. However no such thermally-
9 induced damaged zone has been observed; in fact a reduction of permeability has been
10 observed in the rock affected by temperature increase

11 – there is no perceptible coupling from hydraulic and mechanical phenomena to thermal
12 behaviour. Practically all heat transport is by conduction and the thermal conductivity
13 of the material does not change as deformations are small the material remains
14 saturated throughout. In addition, mechanical energy dissipation is negligible in a non-
15 isothermal case.

17 **Acknowledgements**

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20 Research Centre, Mol, Belgium for their comments and suggestions.

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1 **Figure captions**

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3 Figure 1. Geological profile of the Mont Terri rock laboratory site

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5 Figure 2. Coupled Thermo-hydro-mechanical (THM) phenomena

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7 Figure 3. Location of the main heating tests performed in the Mont Terri rock laboratory

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9 Figure 4. Central borehole layout and location of the central and instrumentation boreholes in
10 the niche. Experiment HE-B.

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12 Figure 5. Distributions of Opalinus Clay temperatures at various times during the heating
13 period. Experiment HE-B.

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15 Figure 6. Thermal-induced pore pressures in Opalinus Clay measured in boreholes BHE-19
16 and BHE-20 (see Figure3). Experiment HE-B.

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18 Figure 7. Schematic layout of the in-situ test HE-D. Locations of observations boreholes are
19 shown.

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21 Figure 8. Evolution of temperature at different distances of the heater axis. Experiment HE-D.

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1 Figure 9. Evolution of thermally-induced pore pressures at different distances of the heater
2 axis. Experiment HE-D.
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17 8 Figure 12. Evolution of temperatures in Opalinus Clay in the vicinity of Heater 1. HE-E
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25 11 Figure 13. Evolution of thermally-induced pore pressures in Opalinus Clay. HE-E experiment
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30 13 Figure 14. Thermal conductivity pairs that result in an error of less than 2% computed at
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32 different times since the start of heating. Figure 13. Thermal conductivity pairs that result in
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34 an error of less than 2% computed at different times since the start of heating. Point heat
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36 source case.
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43 18 Figure 15. Best fitting thermal conductivity pairs for different sensors in the HE-D test. The
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45 stars indicate the average thermal conductivity values for two different hypotheses of heating
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47 power. The parameter α in the Figure indicates anisotropy ratio; the curves corresponding to
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49 constant values of equivalent thermal conductivity, λ_0 , are also shown.
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54 23 Figure 16. Evolution of temperature and pore pressure in borehole D3 during the HE-D test.
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1 Figure 17. Evolution of pore pressure increments at various points in the Opalinus Clay
2 during the HE-D test. Observations and computed results a) Borehole D03, b) Borehole D14,
3 c) Borehole D15, d) Borehole D16, e) Borehole D17, f) Sensor location
4
5 Figure 18. Computed pore pressure increment distributions at various times on a section
6 across Heater 2 in the HE-D test. a) Bedding plane direction b) Perpendicular to bedding
7 plane direction
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9 Figure 19. Computed contours of pore pressure increase in the HE-D test. a) 90 days (end of
10 1st heating stage), b) 93 days, c) 110 days (pore pressure maxima), d) 297 days, e) 346 days
11 (start of cooling phase), f) 509 days (end of test).
12
13 Figure 20. Effect on intrinsic permeability on pore pressure evolution. a) Permeability
14 parameters in the range of realistic values. b) Undrained and drained conditions.
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16 Figure 21. Distributions of deformation measured at different times in borehole D5, drilled
17 approximately perpendicular to the main borehole. HE-D test.
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19 Figure 22. Evolution of strain increments at various points in the Opalinus clay (Borehole D5).
20 Observed and computed results. HE-D test.
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1 **Table caption**

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3 Table 1. Features of the main in-situ heating tests performed in the Mont Terri rock laboratory

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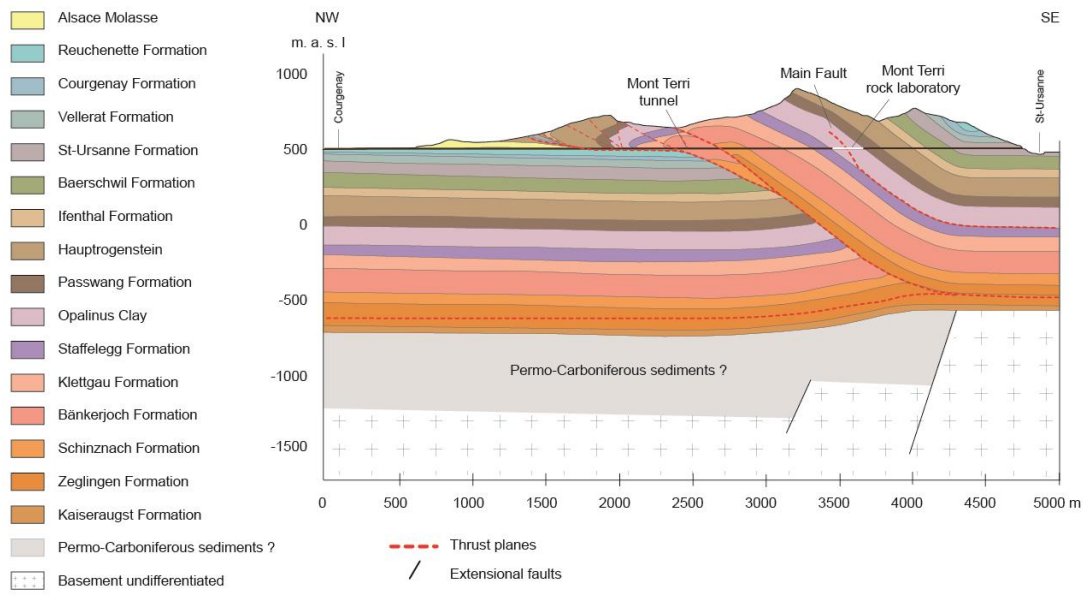


Figure 1. Geological profile of the Mont Terri rock laboratory site

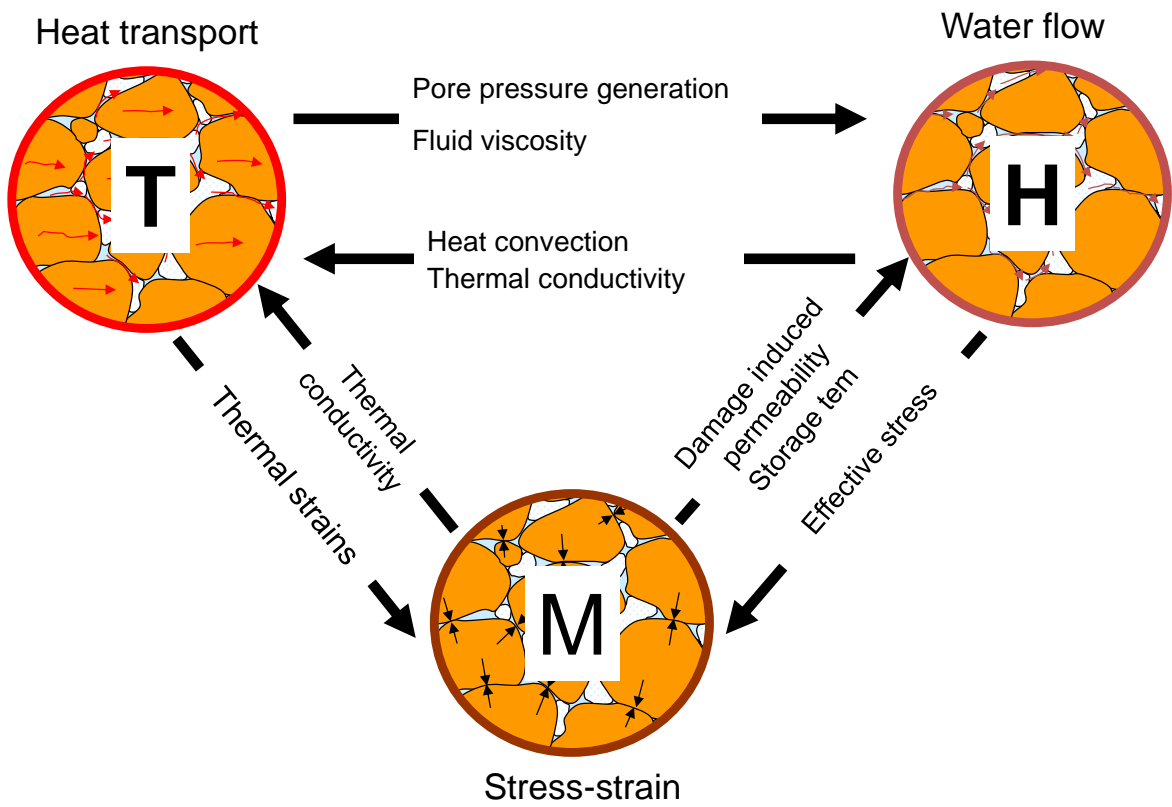


Figure 2. Coupled Thermo-hydro-mechanical (THM) phenomena

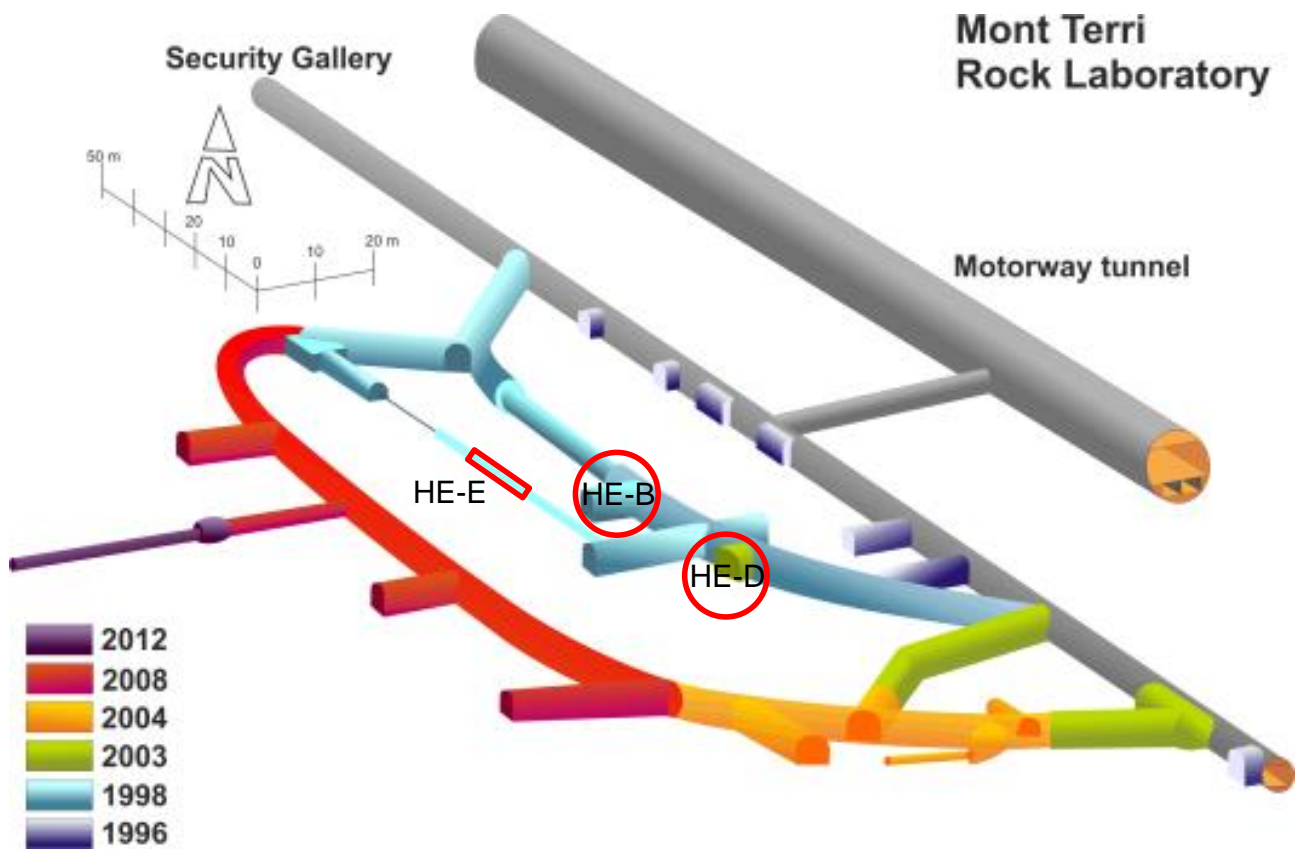


Figure 3. Location of the main heating tests performed in the Mont Terri rock laboratory

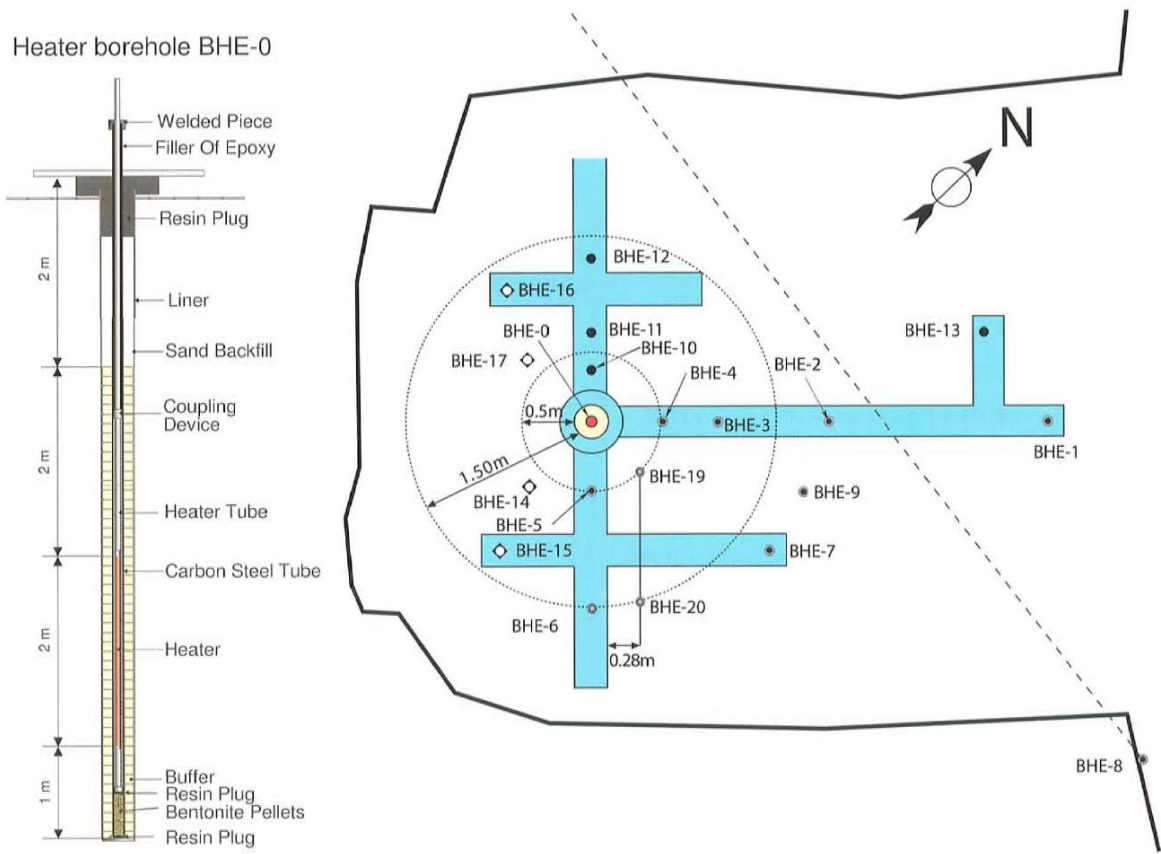


Figure 4. Central borehole layout and location of the central and instrumentation boreholes in the niche. Experiment HE-B.

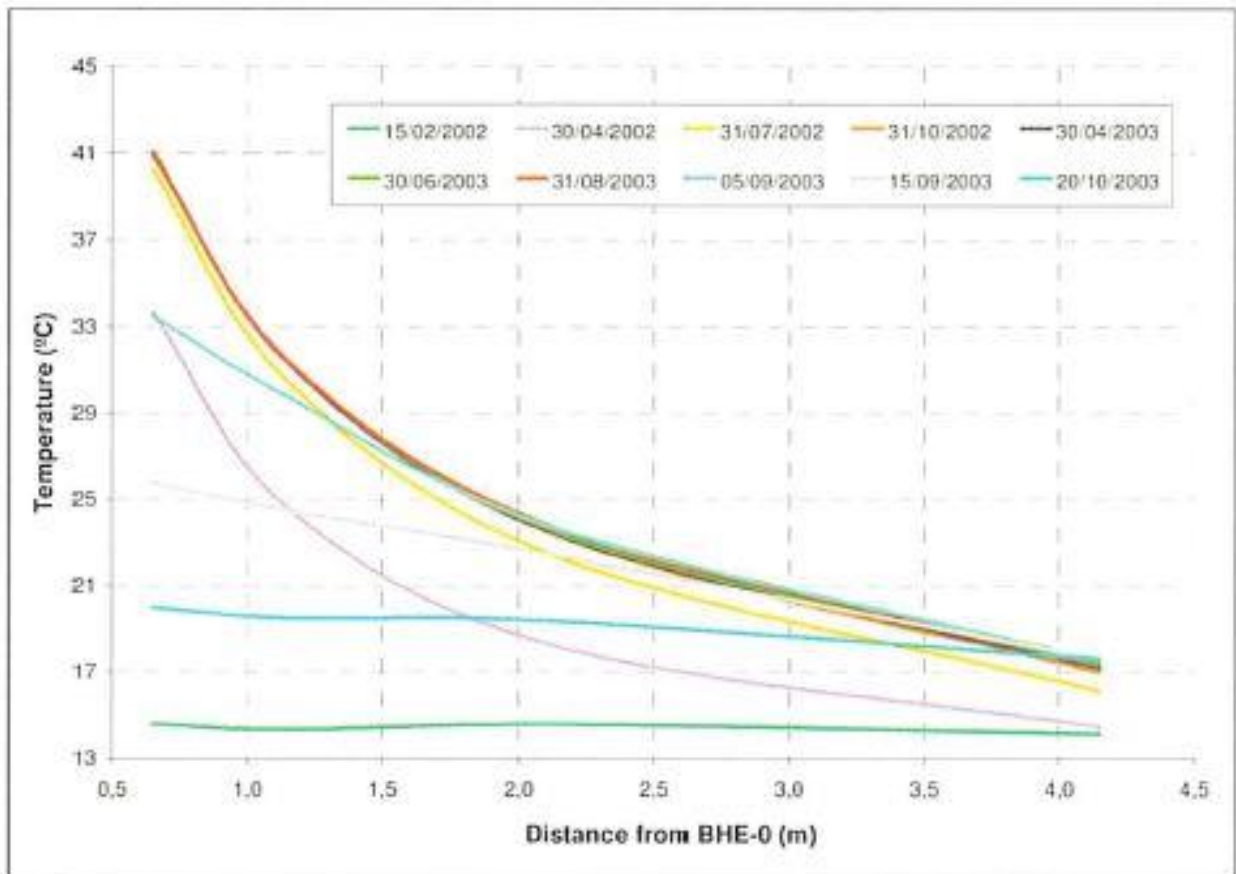


Figure 5. Distributions of Opalinus Clay temperatures at various times during the heating period. Experiment HE-B.

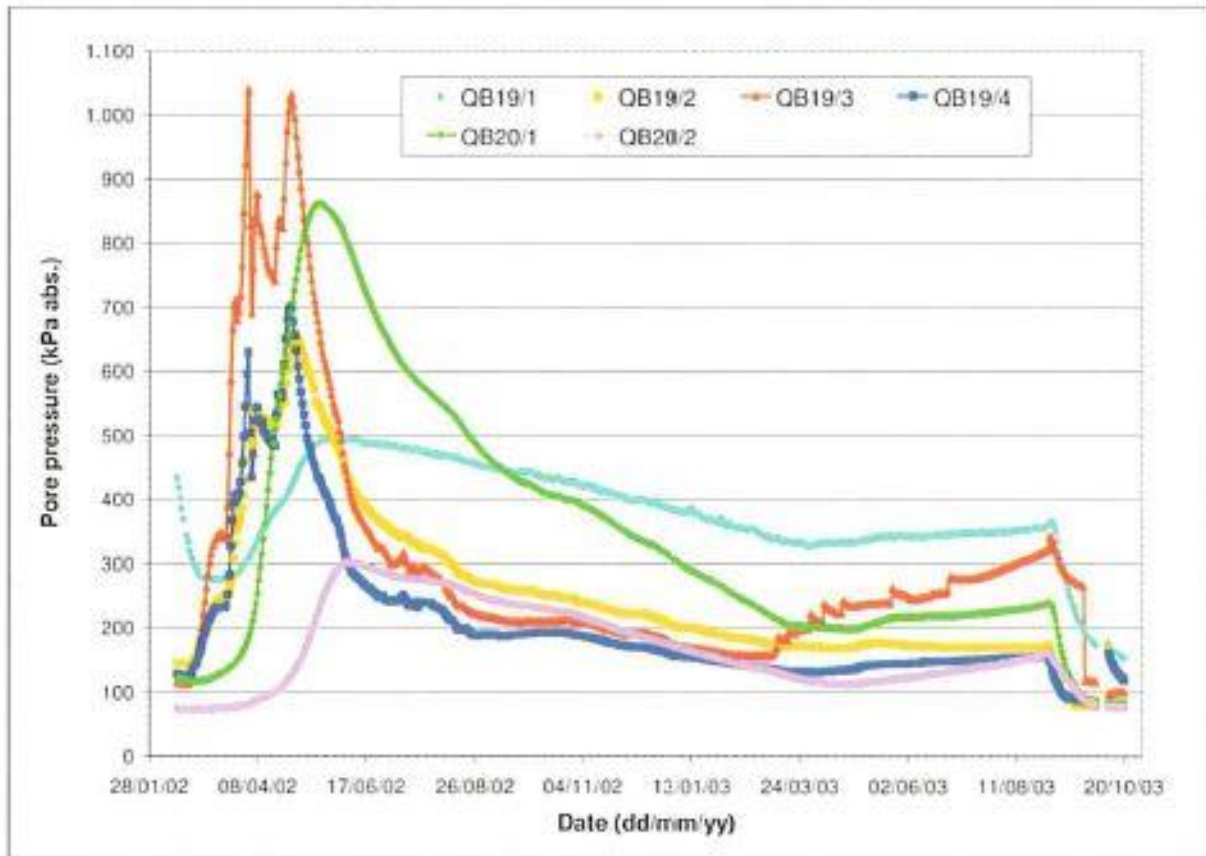


Figure 6. Thermal-induced pore pressures in Opalinus Clay measured in boreholes BHE-19 and BHE-20 (see Figure3). Experiment HE-B.

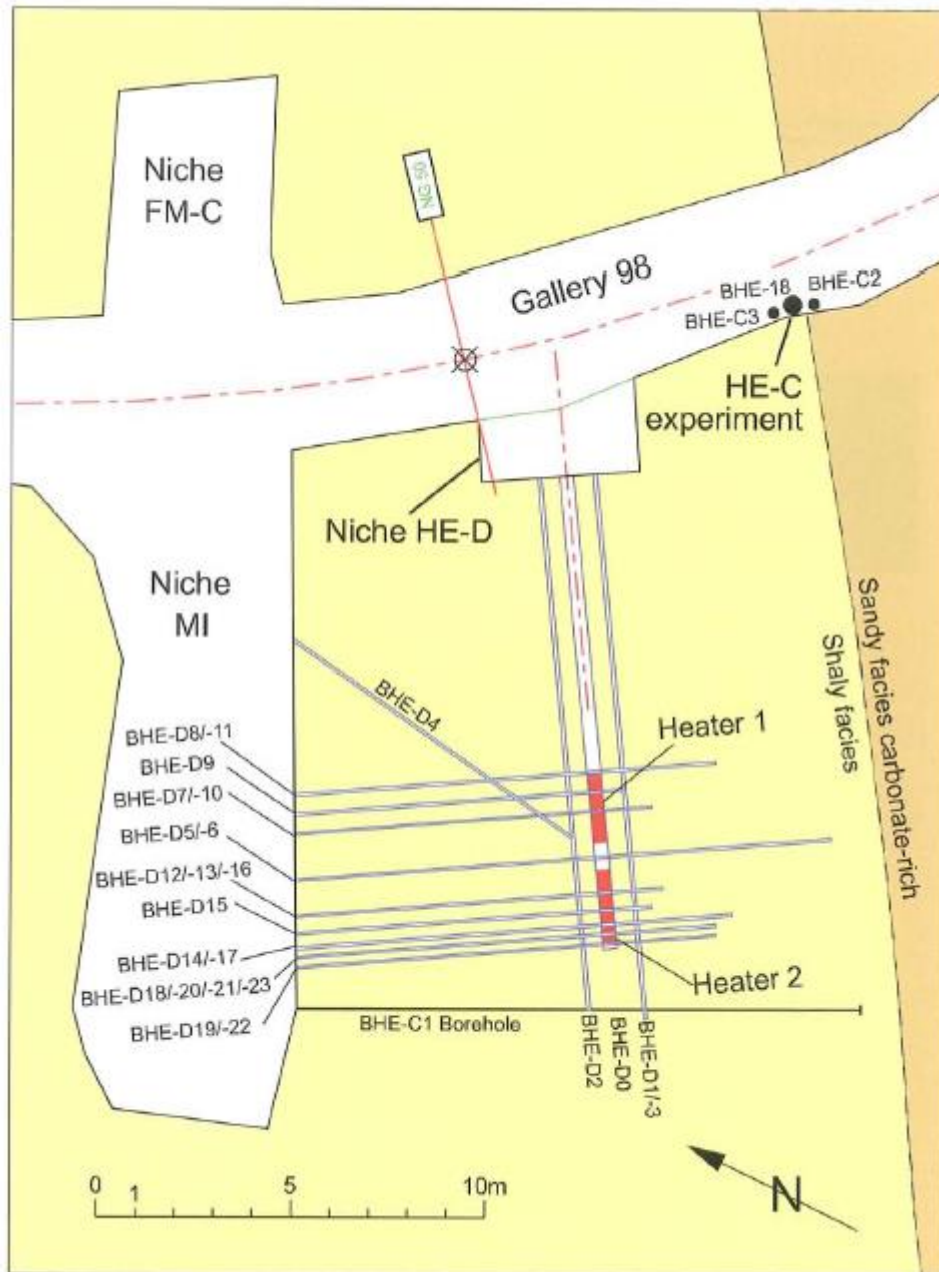


Figure 7. Schematic layout of the in-situ test HE-D. Locations of observations boreholes are shown.

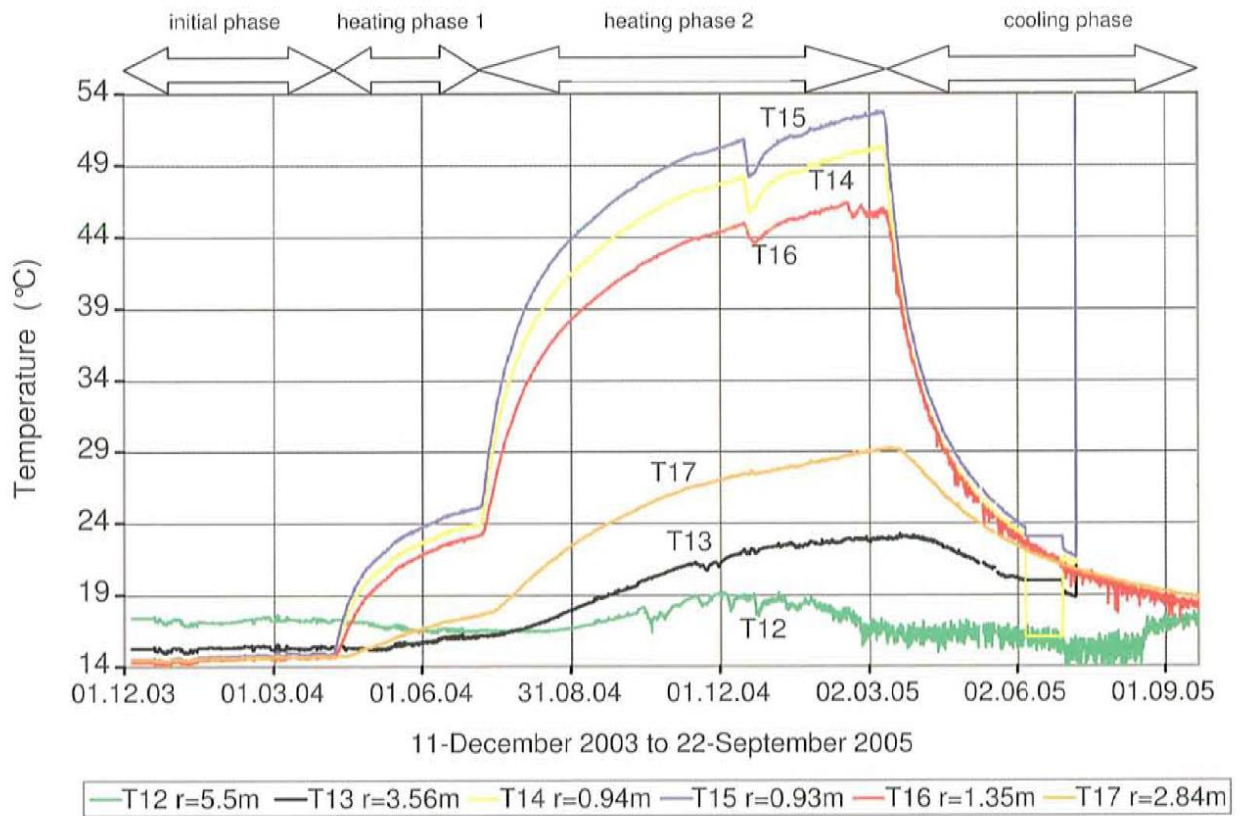


Figure 8. Evolution of temperature at different distances of the heater axis. Experiment HE-D.

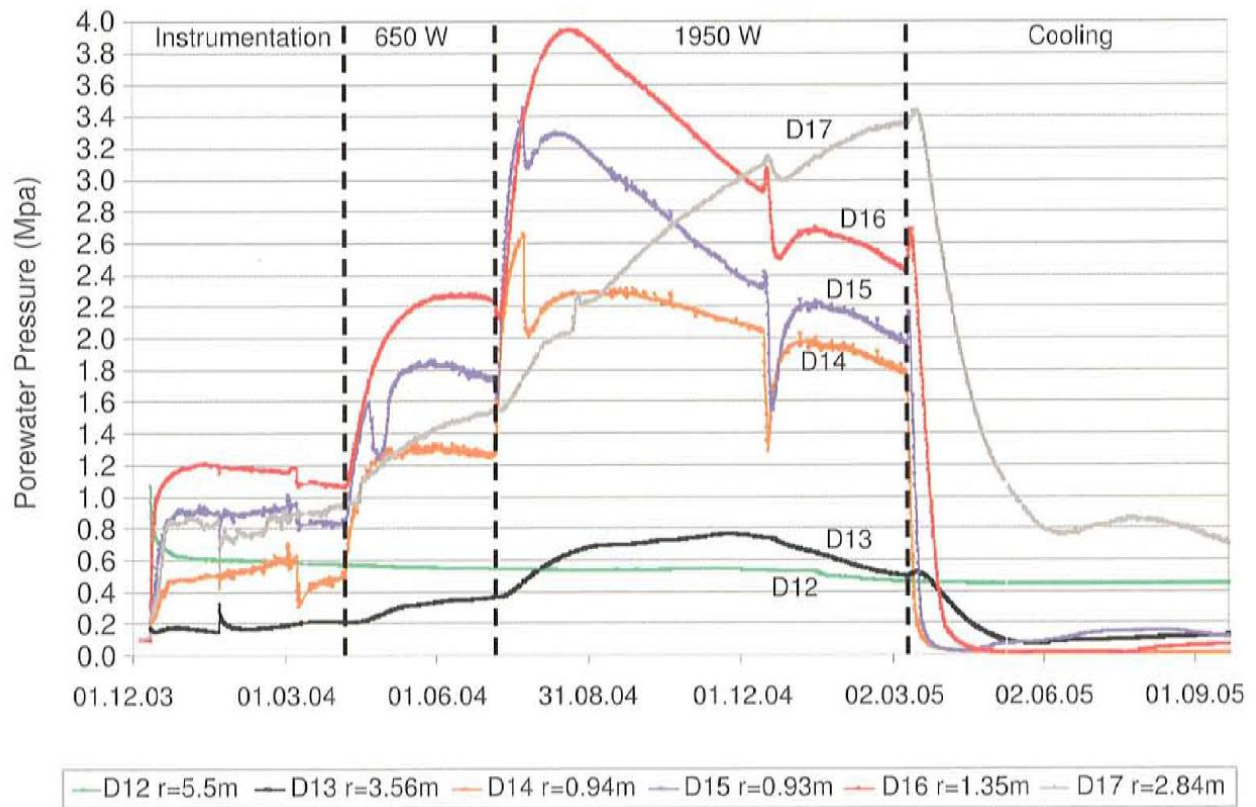


Figure 9. Evolution of thermally-induced pore pressures at different distances of the heater axis. Experiment HE-D.

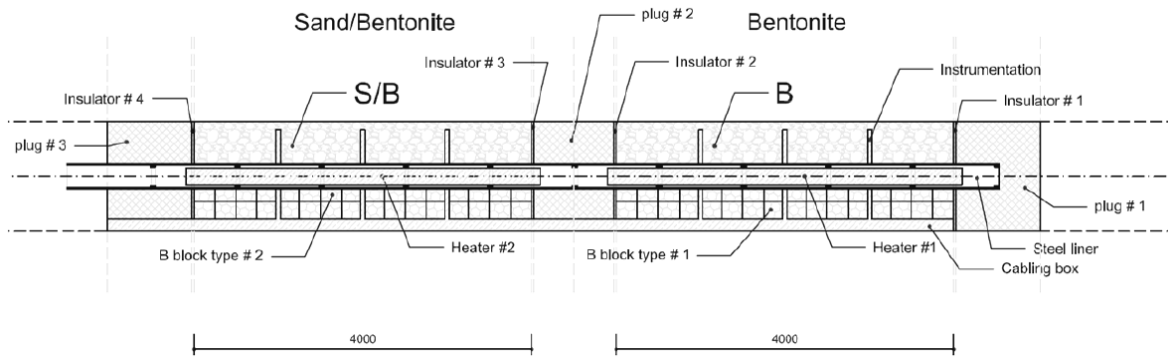


Figure 10. Schematic layout of the HE-E experiment

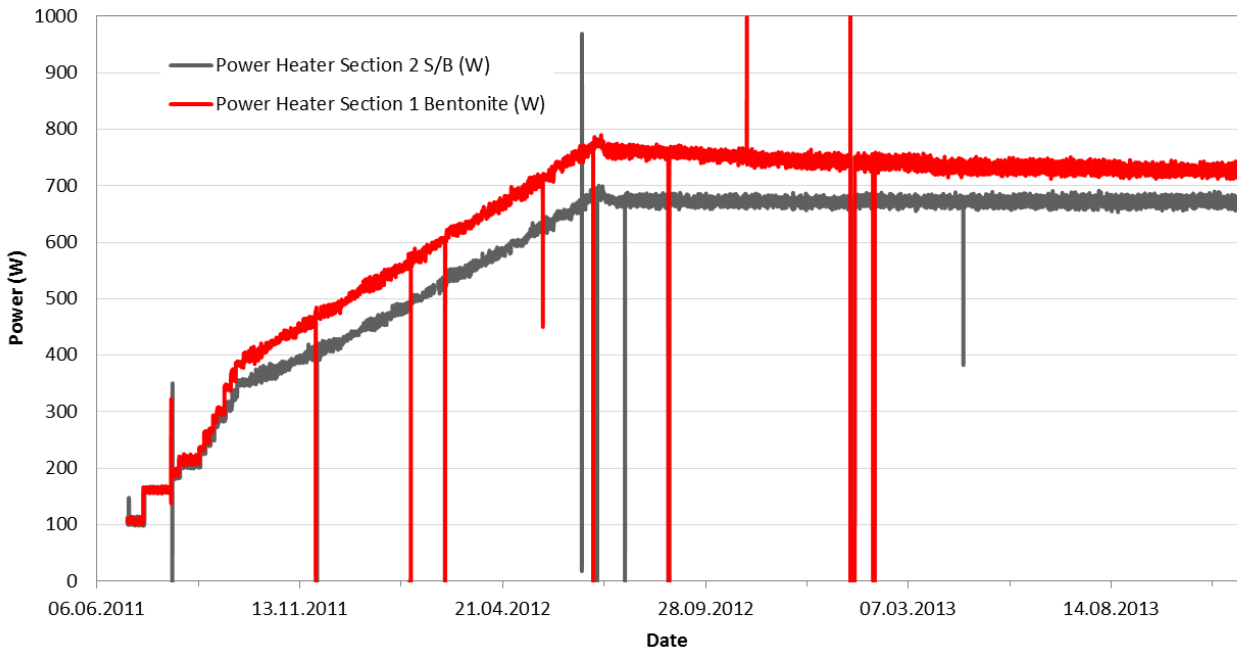


Figure 11. Evolution of the heater power in HE-E experiment

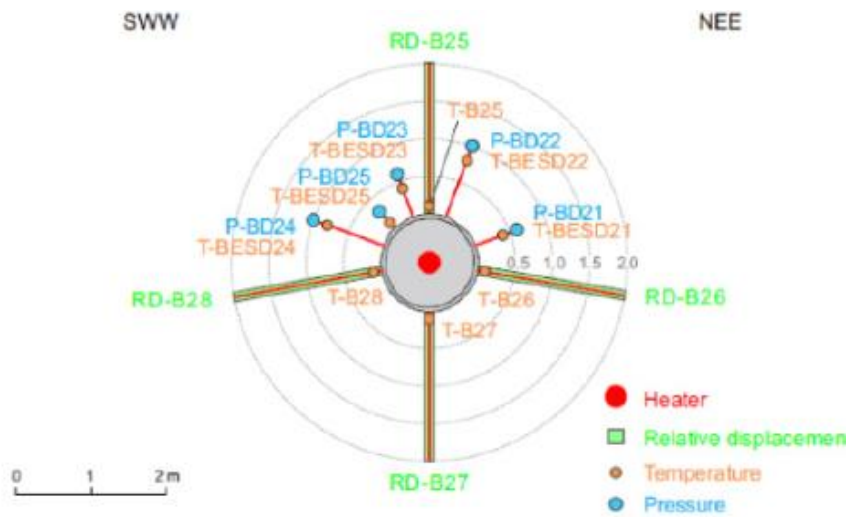
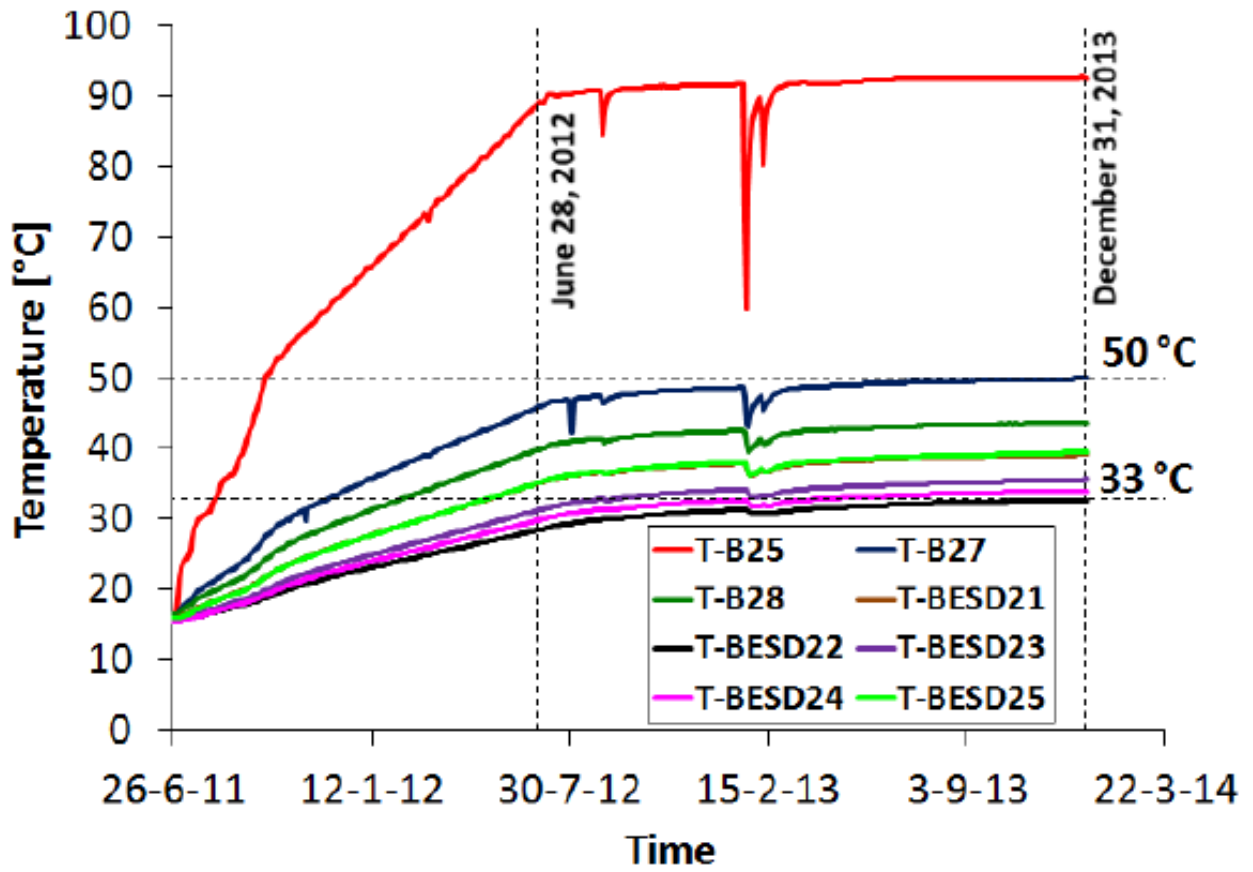


Figure 12. Evolution of temperatures in Opalinus Clay in the vicinity of Heater 1. HE-E experiment

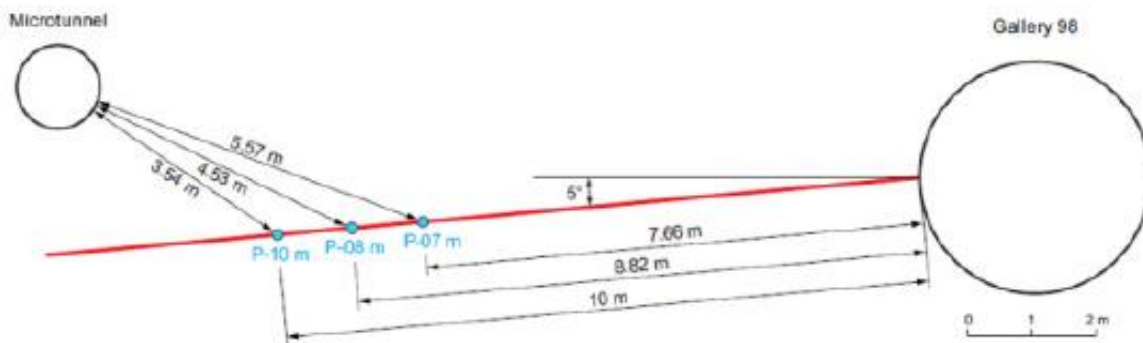
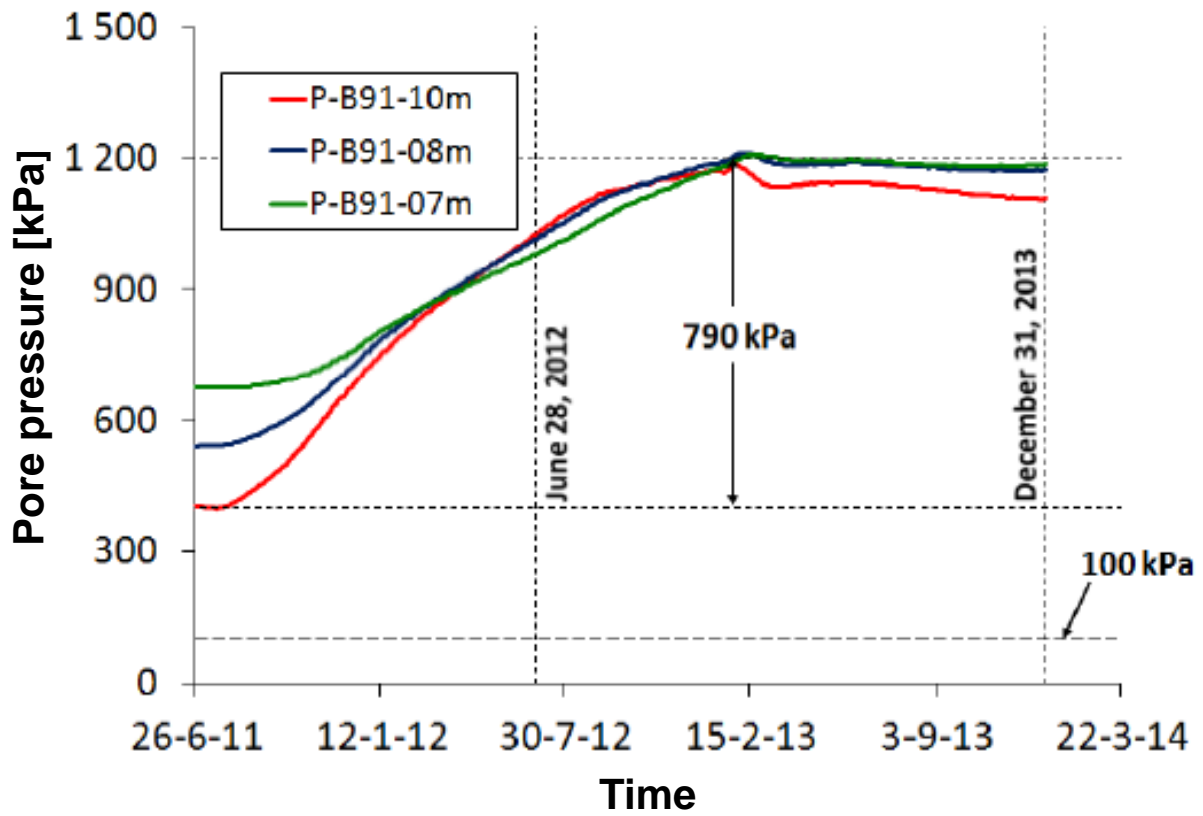


Figure 13. Evolution of thermally-induced pore pressures in Opalinus Clay. HE-E experiment

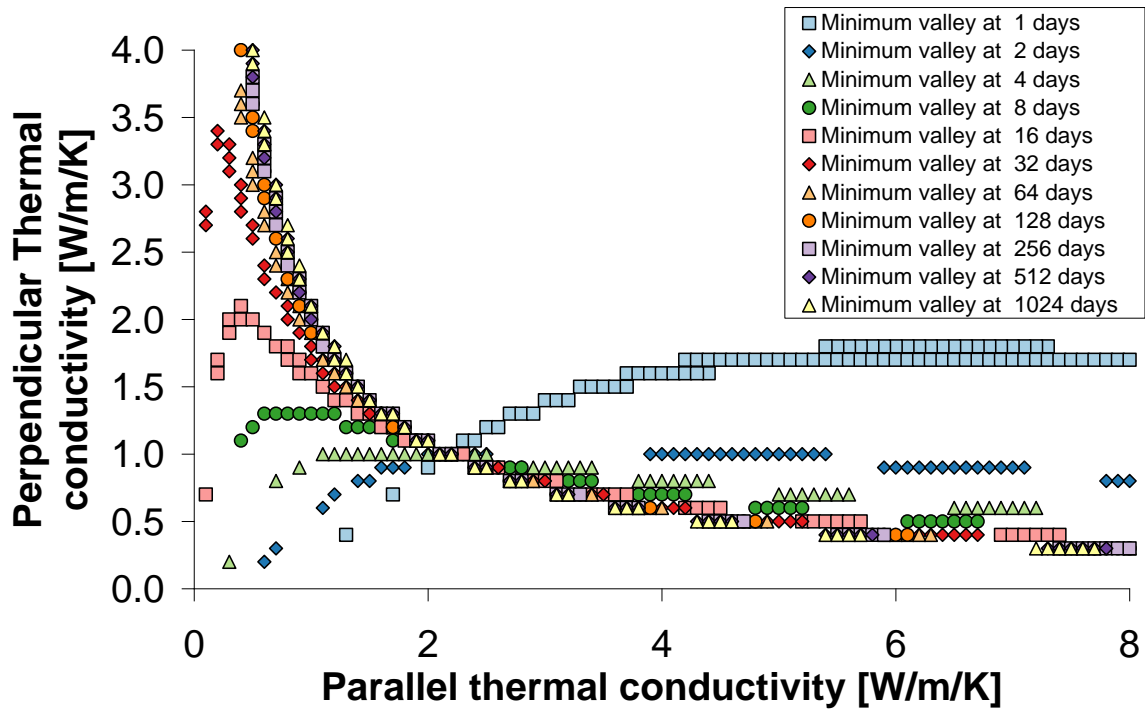


Figure 14. Thermal conductivity pairs that result in an error of less than 2% computed at different times since the start of heating. Point heat source case.

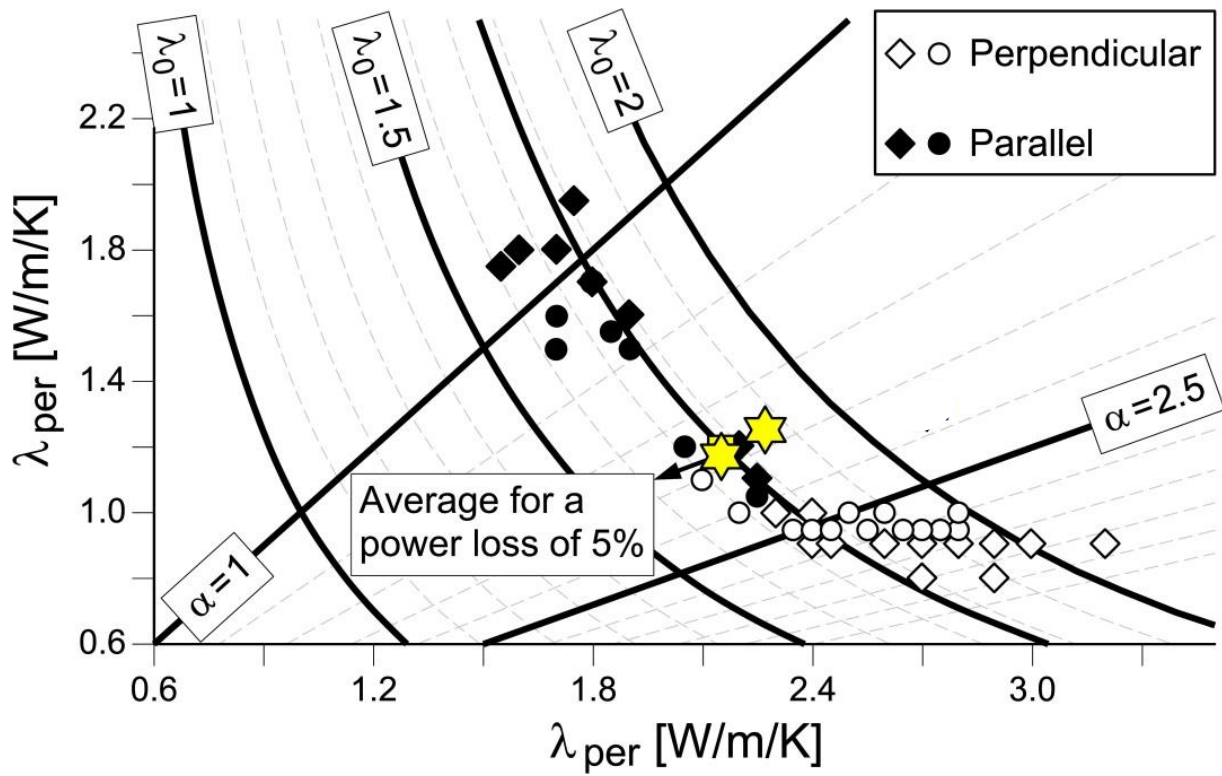


Figure 15. Best fitting thermal conductivity pairs for different sensors in the HE-D test. The stars indicate the average thermal conductivity values for two different hypotheses of heating power. The parameter α in the Figure indicates anisotropy ratio; the curves corresponding to constant values of equivalent thermal conductivity, λ_0 , are also shown.

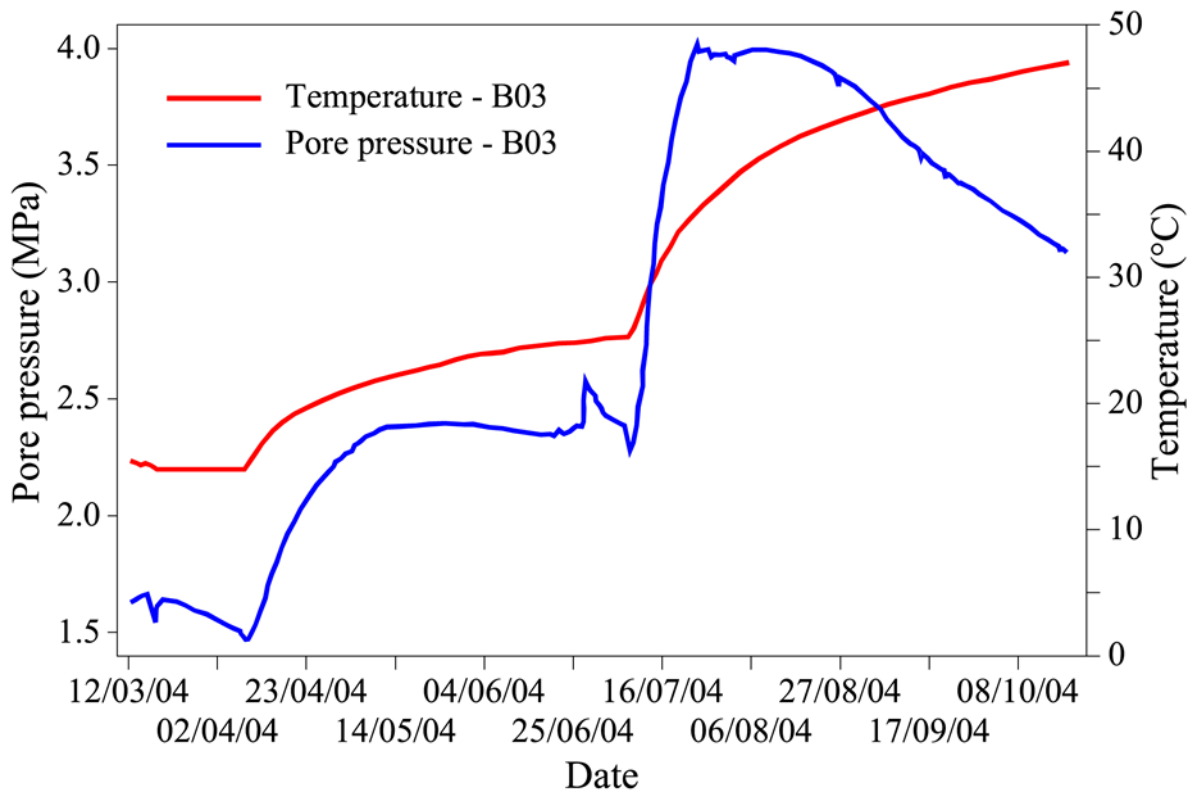
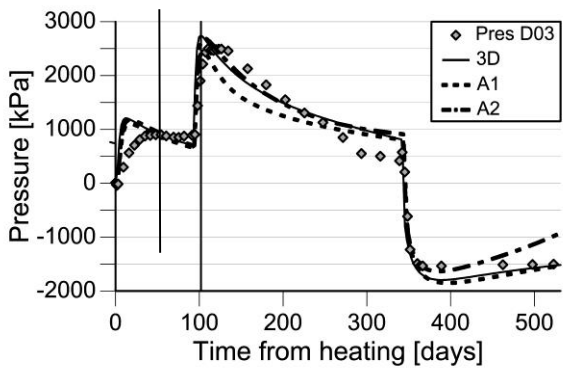
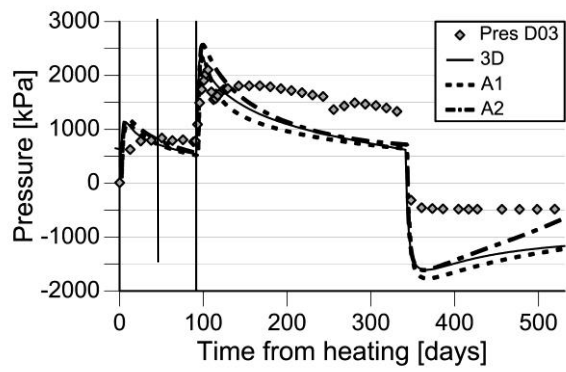


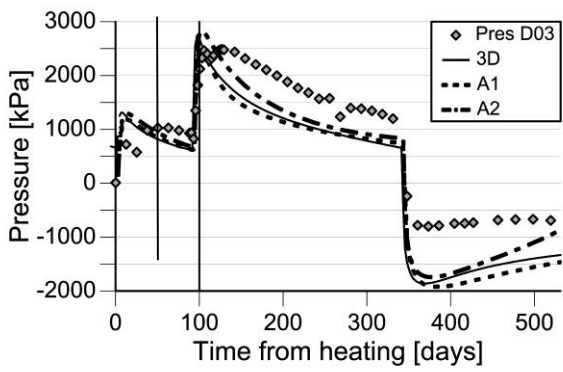
Figure 16. Evolution of temperature and pore pressure in borehole D3 during the HE-D test.



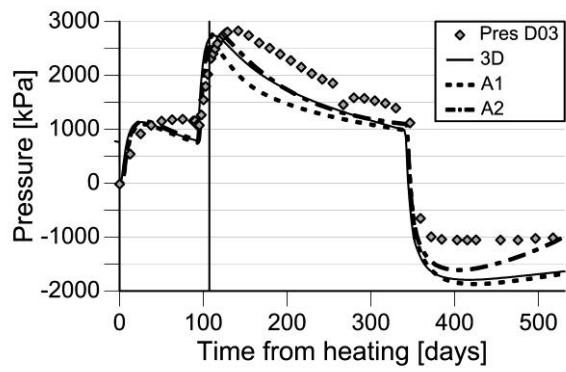
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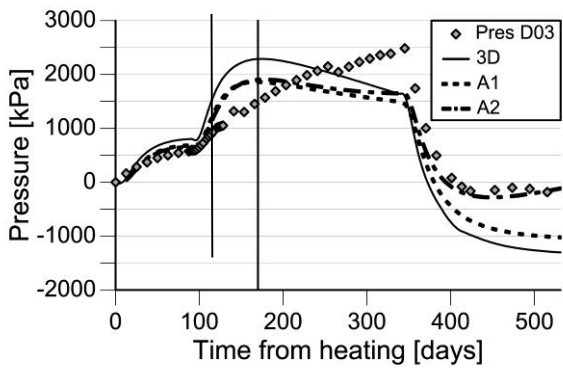
(b)



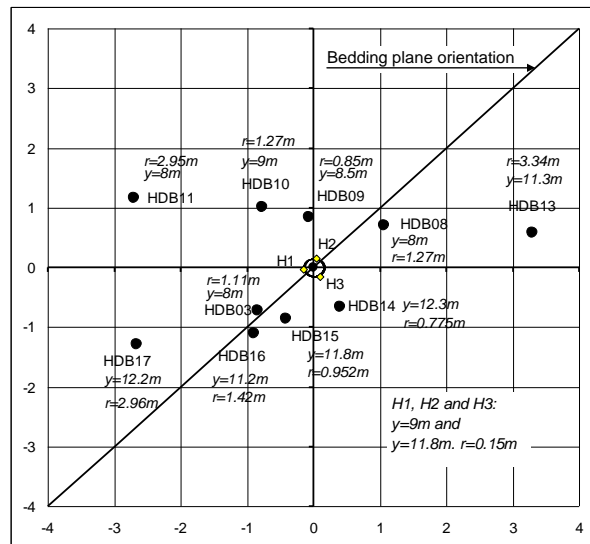
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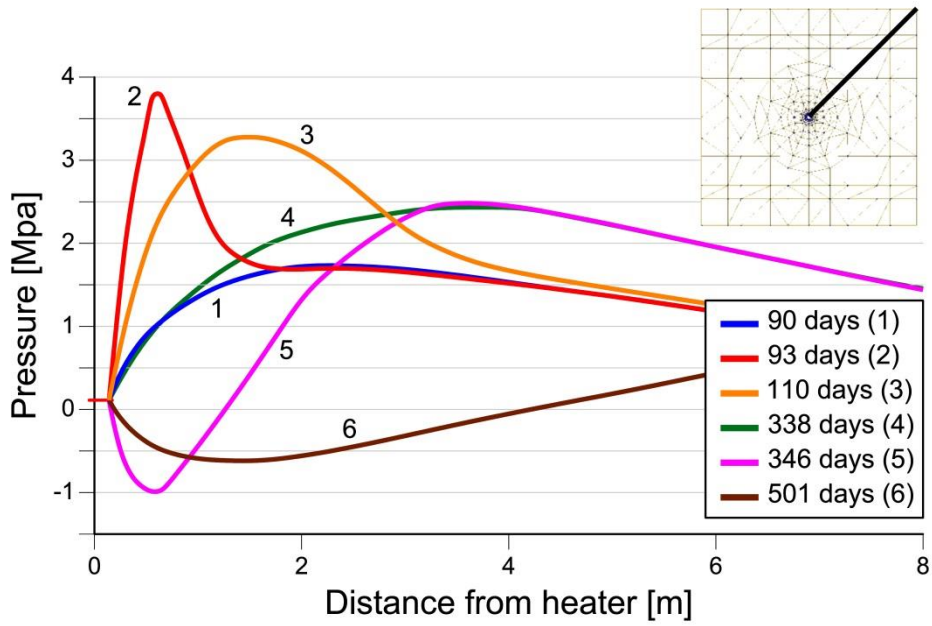


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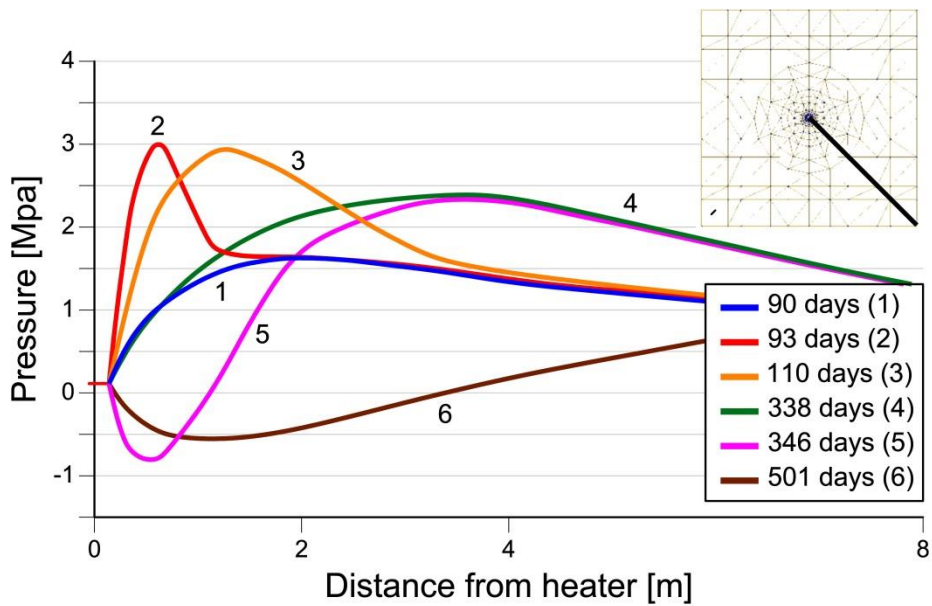


(f)

Figure 17. Evolution of pore pressure increments at various points in the Opalinus Clay during the HE-D test. Observations and computed results a) Borehole D03, b) Borehole D14, c) Borehole D15, d) Borehole D16, e) Borehole D17, f) Sensor location



(a)



(b)

Figure 18. Computed pore pressure increment distributions at various times on a section across Heater 2 in the HE-D test. a) Bedding plane direction b) Perpendicular to bedding plane direction

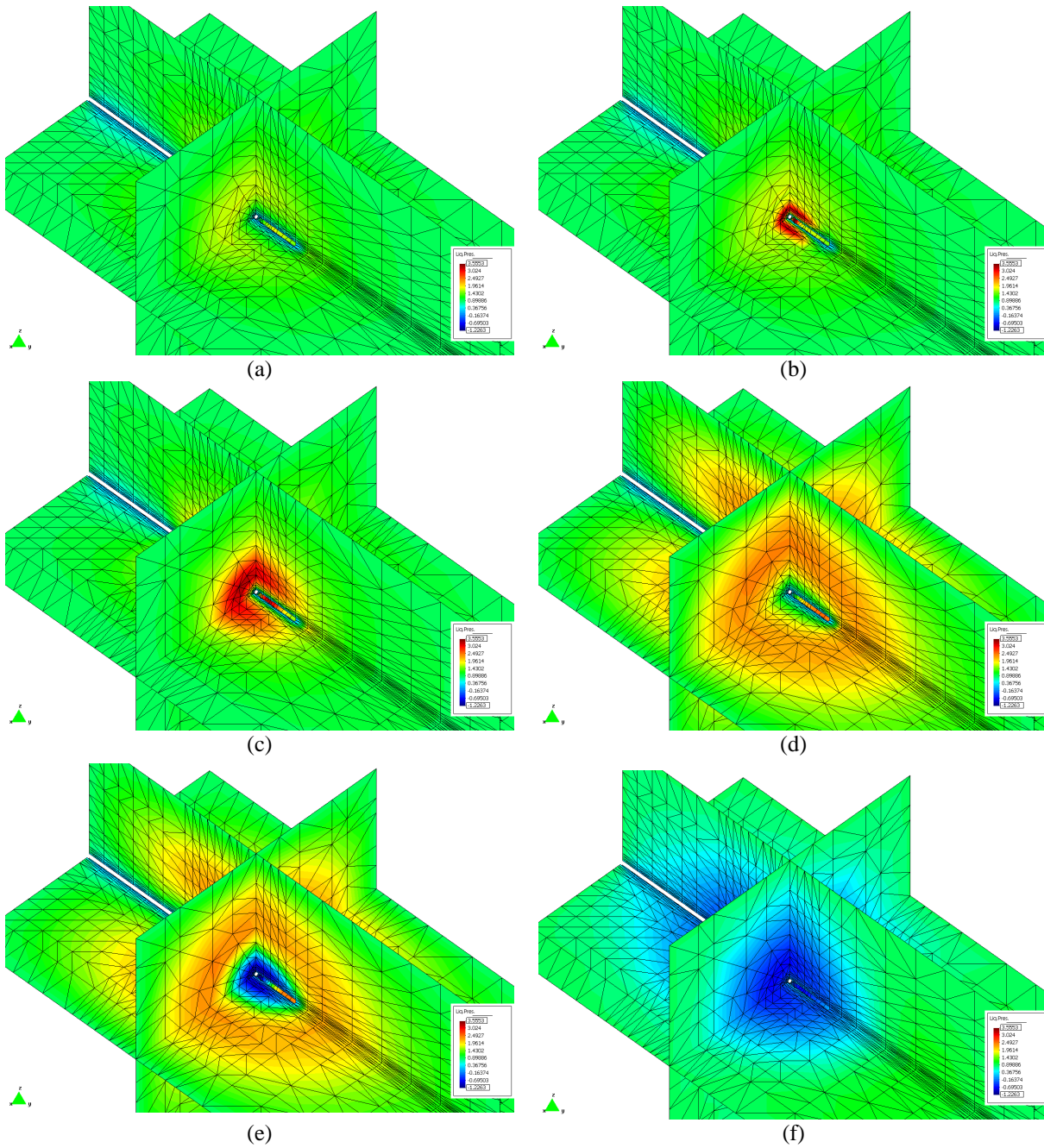
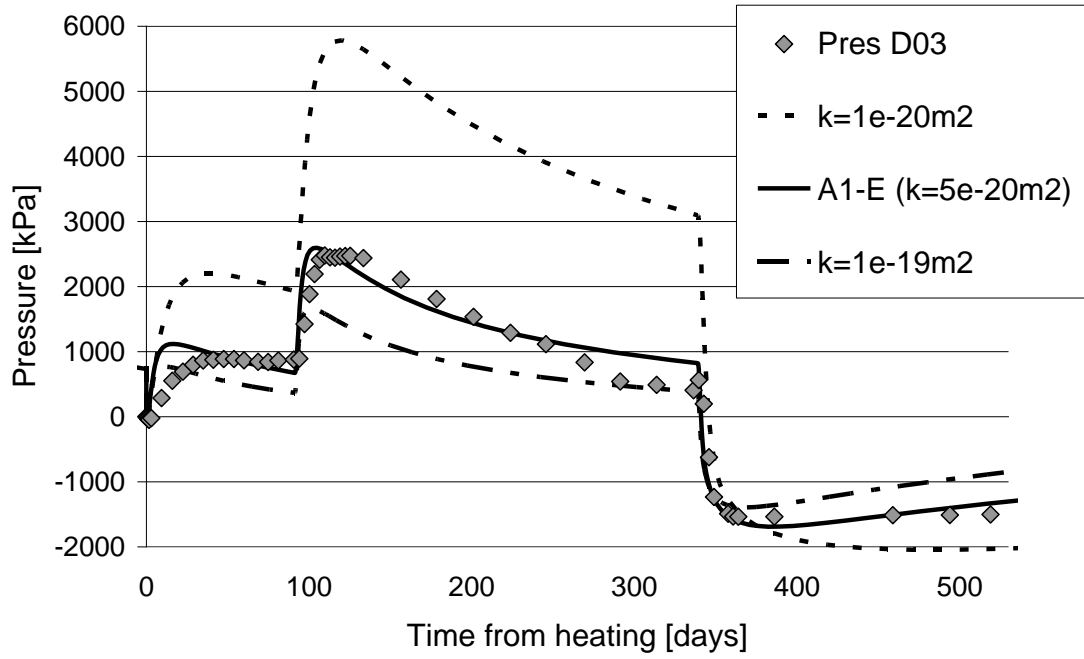
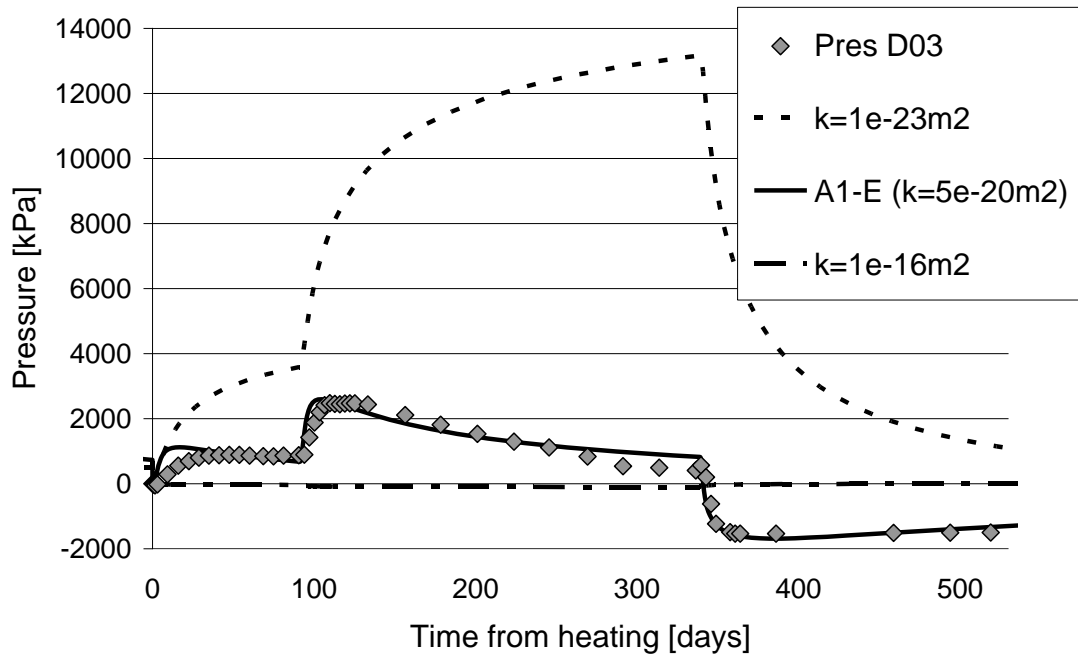


Figure 19. Computed contours of pore pressure increase in the HE-D test. a) 90 days (end of 1st heating stage), b) 93 days, c) 110 days (pore pressure maxima), d) 297 days, e) 346 days (start of cooling phase), f) 509 days (end of test).



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Figure 20. Effect on intrinsic permeability on pore pressure evolution. a) Permeability parameters in the range of realistic values. b) Undrained and drained conditions

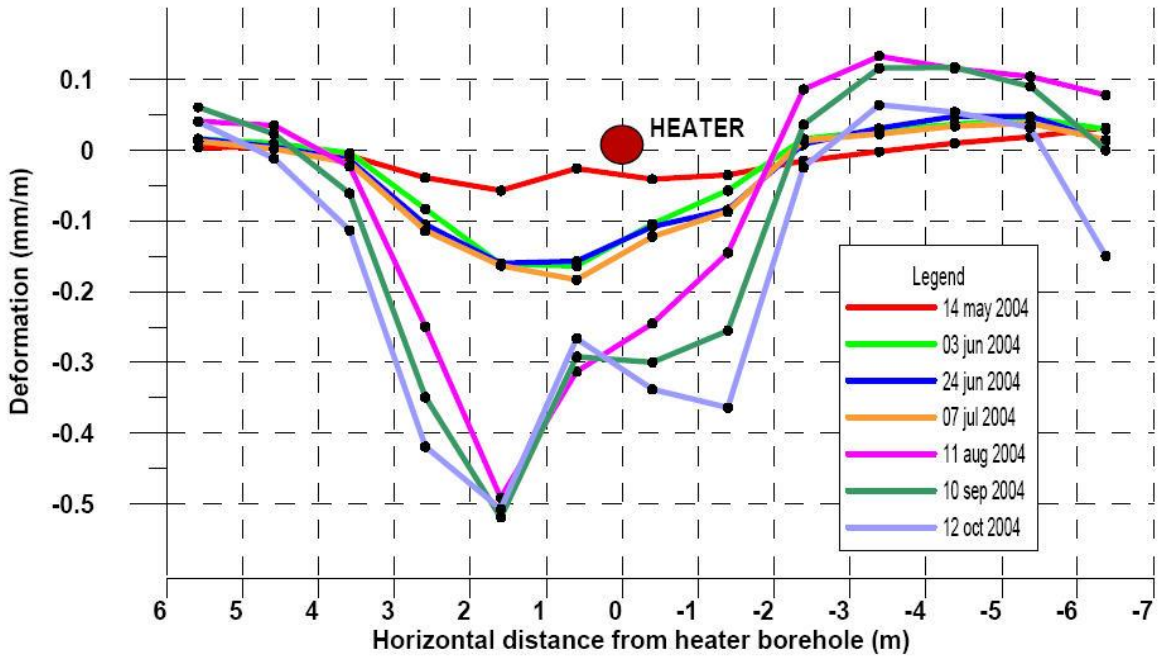
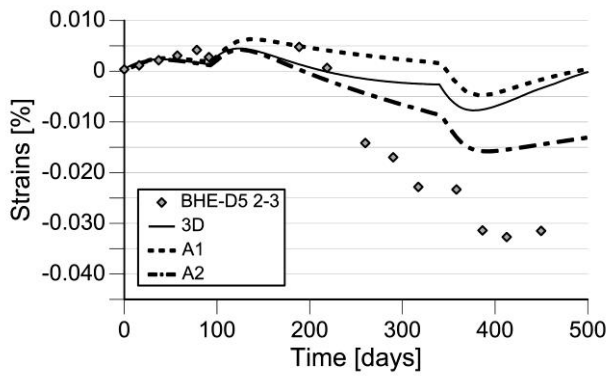
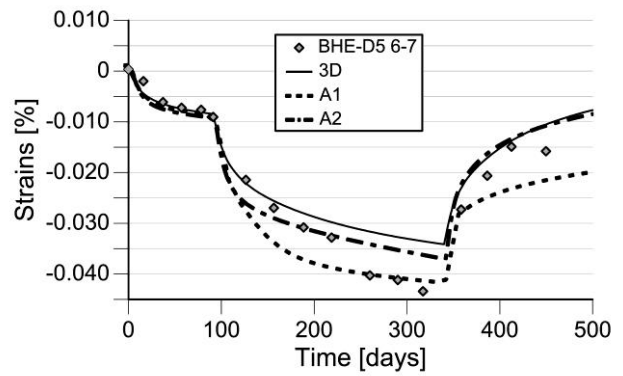


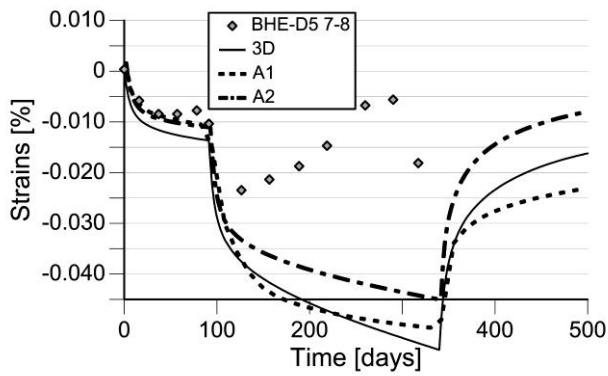
Figure 21. Distributions of deformation measured at different times in borehole D5, drilled approximately perpendicular to the main borehole. HE-D test.



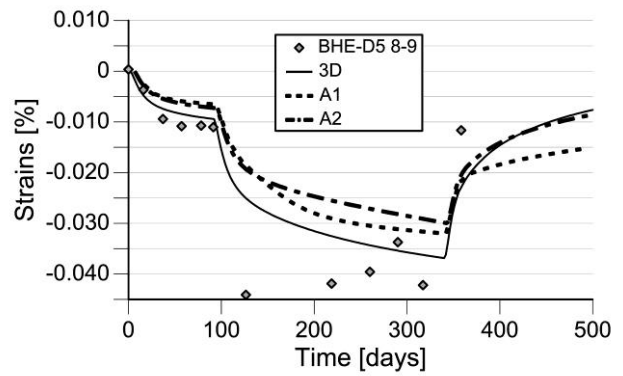
(a)



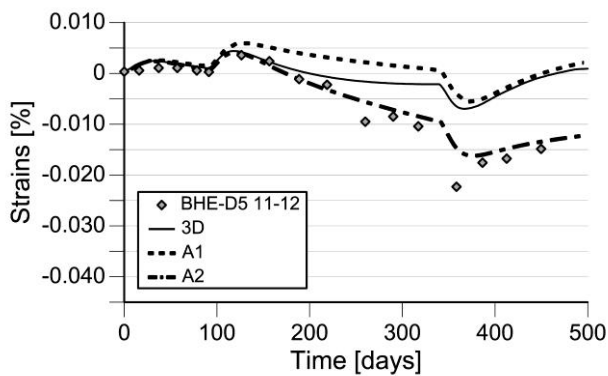
(b)



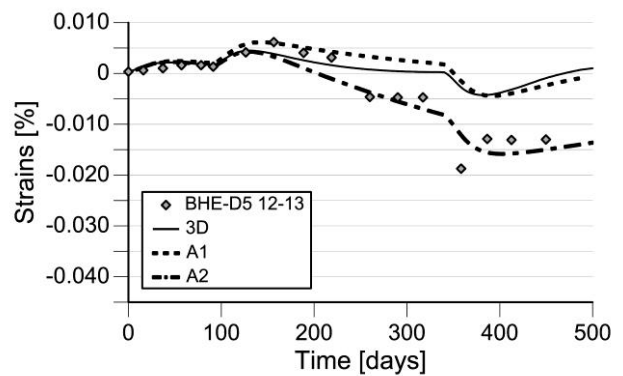
(c)



(d)



(e)



(f)

Figure 22. Evolution of strain increments at various points in the Oplinus clay (Borehole D5). Observed and computed results. HE-D test.

Experiment	HE-B (HE)	HE-D	HE-E
Borehole /Tunnel	Vertical	Horizontal	Horizontal
Borehole /Tunnel diameter	0.3 m	0.3 m	1.3 m
Heater/liner diameter	0.1 m	0.3 m	0.3 m
Heater length	2.02 m	2 x 2 m	2 x 4 m
Max. heater temperature	100°C	100°C	140°C
Backfill thickness	0.1 m	-	0.5 m
Backfill material	Compacted blocks (Febex bentonite)	-	Granular bentonite (MX80, MX80+sand)
Backfill hydration	Artificial	-	Natural
Heating duration	18 months	11 months	Long term
Heating period	February 2002 – August 2003	March 2004 – February 2005	June 2011 - ?

Table 1. Features of the main in-situ heating tests performed in the Mont Terri rock laboratory