FORGE

Fate Of Repository Gases

European Commission FP7

Compilation of Existing Data (Mont Terri)

FORGE Report D4.3 and D5.2 – VER 1.0

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Euratom 7th Framework Programme Project: FORGE

EURATOM

Fate of repository gases (FORGE)

The multiple barrier concept is the cornerstone of all proposed schemes for underground disposal of radioactive wastes. The concept invokes a series of barriers, both engineered and natural, between the waste and the surface. Achieving this concept is the primary objective of all disposal programmes, from site appraisal and characterisation to repository design and construction. However, the performance of the repository as a whole (waste, buffer, engineering disturbed zone, host rock), and in particular its gas transport properties, are still poorly understood. Issues still to be adequately examined that relate to understanding basic processes include: dilational versus visco-capillary flow mechanisms; long-term integrity of seals, in particular gas flow along contacts; role of the EDZ as a conduit for preferential flow; laboratory to field up-scaling. Understanding gas generation and migration is thus vital in the quantitative assessment of repositories and is the focus of the research in this integrated, multi-disciplinary project. The FORGE project is a pan-European project with links to international radioactive waste management organisations, regulators and academia, specifically designed to tackle the key research issues associated with the generation and movement of repository gasses. Of particular importance are the long-term performance of bentonite buffers, plastic clays, indurated mudrocks and crystalline formations. Further experimental data are required to reduce uncertainty relating to the quantitative treatment of gas in performance assessment. FORGE will address these issues through a series of laboratory and field-scale experiments, including the development of new methods for up-scaling allowing the optimisation of concepts through detailed scenario analysis. The FORGE partners are committed to training and CPD through a broad portfolio of training opportunities and initiatives which form a significant part of the project.

Further details on the FORGE project and its outcomes can be accessed at www.FORGEproject.org.

Compilation of Existing Data (Mont Terri) For Forge WP4/Task 4.3 and WP5/Task 5.2.2 Forge Deliverables D4.3 and D5.2

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1 Introduction

This report documents the compilation of existing data from the Mont Terri Project provided to participants in FORGE WP 4.3 and WP 5.2.2. Information relating to the HG-A experiment (considered within FORGE WP 4.3) and HG-C experiment (considered within FORGE WP 5.2.2) are presented within the same documents as there is significant overlap between the two tasks and some modelling teams are involved in both WP 4.3 and WP 5.2.2. The modelling teams are working within a joint HG-A/HG-C modelling group coordinated by Nagra.

The document is organised, in four sections:

- Introduction
- Information on properties of the Opalinus Clay and laboratory testing.
- Information on the HG-A experiment.
- Information on the HG-C experiment.

In addition two short appendices describe the data formats used to deliver HG-A and HG-C field test data.

This report corresponds to deliverables:

D4.3 Report – compilation of existing data (Mont Terri) WP4.2.1

D5.2 Design, installation and compilation of existing data for the HG-C experiment at Mont Terri WP5.2.2

2 Properties of the Opalinus Clay at Mont Terri

The modelling teams have been provided with both reference properties and laboratory test data to help them develop suitable constitutive models for the Opalinus Clay at Mont Terri. This chapter lists the reference properties and provides a brief description of some of the laboratory testing. Full descriptions of the laboratory testing were provided in reports distributed to the modellers.

2.2 Reference properties and stresses

2.2.1 Reference mechanical properties

Reference values have been derived for selected mechanical properties of the intact Opalinus at Mont Terri in previous projects – nevertheless some of the parameters are still under discussion. The reasons for the considerable uncertainty in reported mechanical parameters are not fully understood (variability in mineralogy/lithology, uncertainties in measuring techniques, etc.). A summary table of the reference values is given below.

Table 1: Geotechnical reference parameters of the Opalinus Clay at the Mont Terri underground laboratory after (Bock 2000).

Parameter	Value	Remarks
Bulk density [Mg/m^3]	2.45	
Grain density [Mg/m^3]	2.71	
Porosity [%]	13.7	Range: 10 - 16 %
Water content [% wt]	6.1	Range: 6 - 7 %
Young's modulus [GPa]	10 4	parallel to bedding normal to bedding
Shear modulus	1.2	
Poisson's ratio [-]	0.27	
Uniaxial compressive strength [MPa]	10 16	parallel to bedding normal to bedding
Tensile strength [MPa]	2 1	parallel to bedding normal to bedding
P-wave velocity [m/s]	3410 2620	parallel to bedding normal to bedding
S-wave velocity [m/s]	1960 1510	parallel to bedding normal to bedding
Fracture toughness [MN/m$^{1.5}$]	0.53 0.12	K_{IC} parallel to bedding K_{IC} normal to bedding

2.2.2 Hydraulic properties of the Opalinus Clay at Mont Terri

Marschall et al (2004) describe a conceptual model of groundwater flow in the Opalinus at Mont Terri and note that at the core scale "layering can be interpreted as an indication for pronounced anisotropy of the hydraulic conductivity at the centimetre and decimetre scale." They provide information on permeameter tests on core from Mont Terri and packer tests performed at Mont Terri. Packer test hydraulic conductivity ranged from 2×10^{-14}-2×10^{-12}m/s. Results from tests in different facies showed some variation, which was thought to be largely due to variations in testing and which could not be used to identify systematic variations in conductivity between the different facies. Summary hydraulic conductivity values are given in Table 2. A limited number of permeameter tests were performed and the database is insufficient to estimate the hydraulic anisotropy.

Table 2 Range of hydraulic properties for different facies of the Opalinus Clay at Mont Terri (from Marschall et al 2004).

Scale	Facies	Hydraulic conductivity (m/s)	Specific storage (1/m)
0.1m-10m	Carbonate rich sandy facies	4×10^{-13}-9×10^{-13}	2×10^{-7}-6×10^{-7}
	Sandy facies	2×10^{-14}-2×10^{-13}	-
	Shaly facies	2×10^{-14}-2×10^{-12}	3×10^{-7}-3×10^{-5}

Nagra (2002) presents results from permeability and diffusion tests on Opalinus Clay core from the Benken boreholes (Zürcher Weinland). Nagra (2002) suggests a range of "anisotropy factor" $K_{\equiv}/K_{\perp}$ of between 1 and 10. The anisotropy in the diffusion constant was found to be about a factor of 5. Microscopic observation of the fabric of the Opalinus Clay at Mont Terri suggests that there may be a significant core-scale hydraulic anisotropy. However the database of permeameter tests on core from Mont Terri is insufficient to provide robust estimates of hydraulic anisotropy of the Opalinus Clay. The value of the anisotropy factor $K_{\equiv}/K_{\perp}$ is thought to lie between 1 and 10, with a suggested value of 5.

2.2.2 Stress State at Mont Terri

Martin & Lanyon (2003a) and Bossart & Wermeille (2003) report results from several stress measurement campaigns at the Mont Terri Rock Laboratory including the results of a previous data compilation by Wermeille & Bossart (1999). Martin & Lanyon (2003a) suggest that the stress tensor given in Table 3 is representative of the stress state at the laboratory although the greatest uncertainty is in the estimate of σ_3. In particular the low range value of 0.6 (derived from analysis of an undercore experiment) is below the best estimate of pore pressure at the laboratory (Marschall et al 2004).

Table 3: Stress tensor for Mont Terri Rock Laboratory (from Martin&Lanyon 2003a and Bossart&Wermeille 2003).

	Martin & Lanyon (2003a)				
	Orientation	Trend (°)	Plunge (°)	Magnitude Estimate	Range (MPa)
σ_1	Vertical	210	70	6.5	6-7
σ_2	NW-SE	320	10	4.0	4-5
σ_3	NE-SW	50	15	0.6	0.6-2

	Bossart&Wermeille (2003)			
	Trend (°)	Plunge (°)	Magnitude Estimate	Range (MPa)
σ_1	210	70	6.5	6-7
σ_2	320	10	4.4	4-5
σ_3	50	20	2.2	2-3

	Corkum & Martin (2007)				
	Orientation	Trend (°)	Plunge (°)	Magnitude Estimate	Range (MPa)
σ_1	Vertical	210	70	6.5	6-7
σ_2	NW-SE	320	7	4.0	4-5
σ_3	NE-SW	52	18	2.2	2-3

More recent studies by Corkum (2007) and Corkum & Martin (2007) led to a revised estimate of σ_3 magnitude as shown in Table 3. Note that there are minor orientation differences[1]. The recommended full tensor for the Mont Terri rock laboratory is that from Corkum & Martin (2007).

More recent studies have involved stress measurements in the surrounding lithologies at Mont Terri to avoid problems of measurement in the anisotropic moisture-sensitive Opalinus (see Martin & Lanyon 2003b for a discussion of the difficulties of measurements in the Opalinus). Results from these studies are not currently available.

2.3 Laboratory testing

A variety of experiments dedicated to gas transport phenomena have been conducted at Mont Terri, including gas permeability tests on core specimen, ventilation tests in tunnels and long-term gas injection experiments in boreholes. The experiments differ substantially in the experimental conditions. Thus, the mechanisms which control gas transport through the rock body may be different for the different experiments.

The laboratory tests considered here include:

- Laboratory test on diffusion dominated gas transport
- Two-phase flow regime: long-term desaturation and gas permeability experiments on core specimen and in-situ gas injection experiments
- Gas injection experiments at high gas pressure

A list of the relevant datasets is given below in Table 4.

Table 4: Laboratory tests on gas transport.

Tests	Prevailing flow regime & features	Setting	Scale (cms)	Gas Pressure (MPa)
Lab Diffusion Test	Diffusion dominated gas transport	Lab Core	Ø=2.4 h≈ 2	1.5
Desaturation/ resaturation	Two-phase flow	Lab Core	Ø=16 h= 20	-
High gas injection pressure	Two-phase flow	Lab Core	Ø=5.4 h=3.4	15

[1] Table 1 and Figure 6 of Corkum & Martin(2007) is in error. The values given in Table 1 are correct.

2.3.1 Laboratory experiments on diffusion dominated gas transport

A total of 6 gas injection and breakthrough tests using either helium or argon gas on small cylindrical samples (Ø 2.4 cm, height 2 cm) of Opalinus Clay from the Mont Terri underground laboratory have been performed by Krooss & Alles (2007). An isostatic cell was used to confine the sample axially and radially with a confining pressure of 6 MPa, which corresponds to the natural stress conditions in the field (Mont Terri, max. principal stress). The experimental procedure starts with a water permeability test performed on each sample followed by the gas injection test. After creating a gas filled volume at each end of the sample, is injected into the upstream compartment (tubing and porous disc) and closed hermetically. The pressure evolution in the two (upstream and downstream) compartments is continuously monitored over time: a steady decrease is observed in the upstream compartment, a steady increase at the downstream compartment. The differences between upstream and downstream gas pressure were kept low (probably below gas entry pressure).

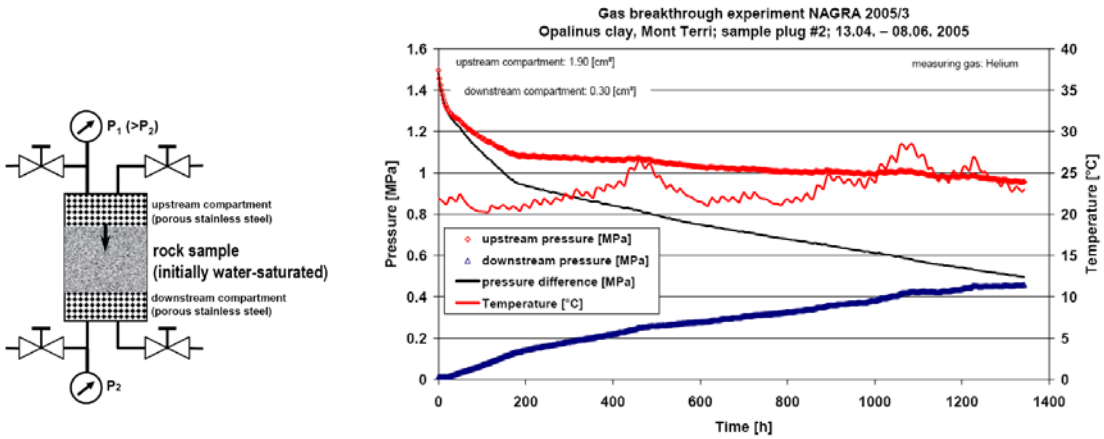

Figure 1: Gas transport experiments on core samples by Krooss&Alles (2007): Sample configuration and experimental results.

A comprehensive description of the experimental configuration and of the test procedures is given in Krooss & Alles (2007).

2.2.2 Two-phase flow experiments

Two different types of experiments have been used to investigate the phenomena, associated with the two-phase flow regime:

- Desaturation / resaturation experiments on large-size core samples
- Gas permeability experiments at elevated gas injection pressure (excess gas pressure > gas entry pressure)

Desaturation / resaturation experiments

Long-term desaturation and saturation experiments were performed on a large drillcore (20cm long, 16 cm diameter) from the Mont Terri URL. The circumferential surface of the core was resin-impregnated and thus the desaturation/saturation processes took place only in the axial direction across the front and end faces of the core. The experiments were conducted in a drying chamber (Figure 2) under well-defined humidity conditions. The weight of the core sample was measured continuously during all test sequences. Figure 2b provides a typical data set from this

experiment, displaying the transients of humidity in the chamber and the weight of the core sample.

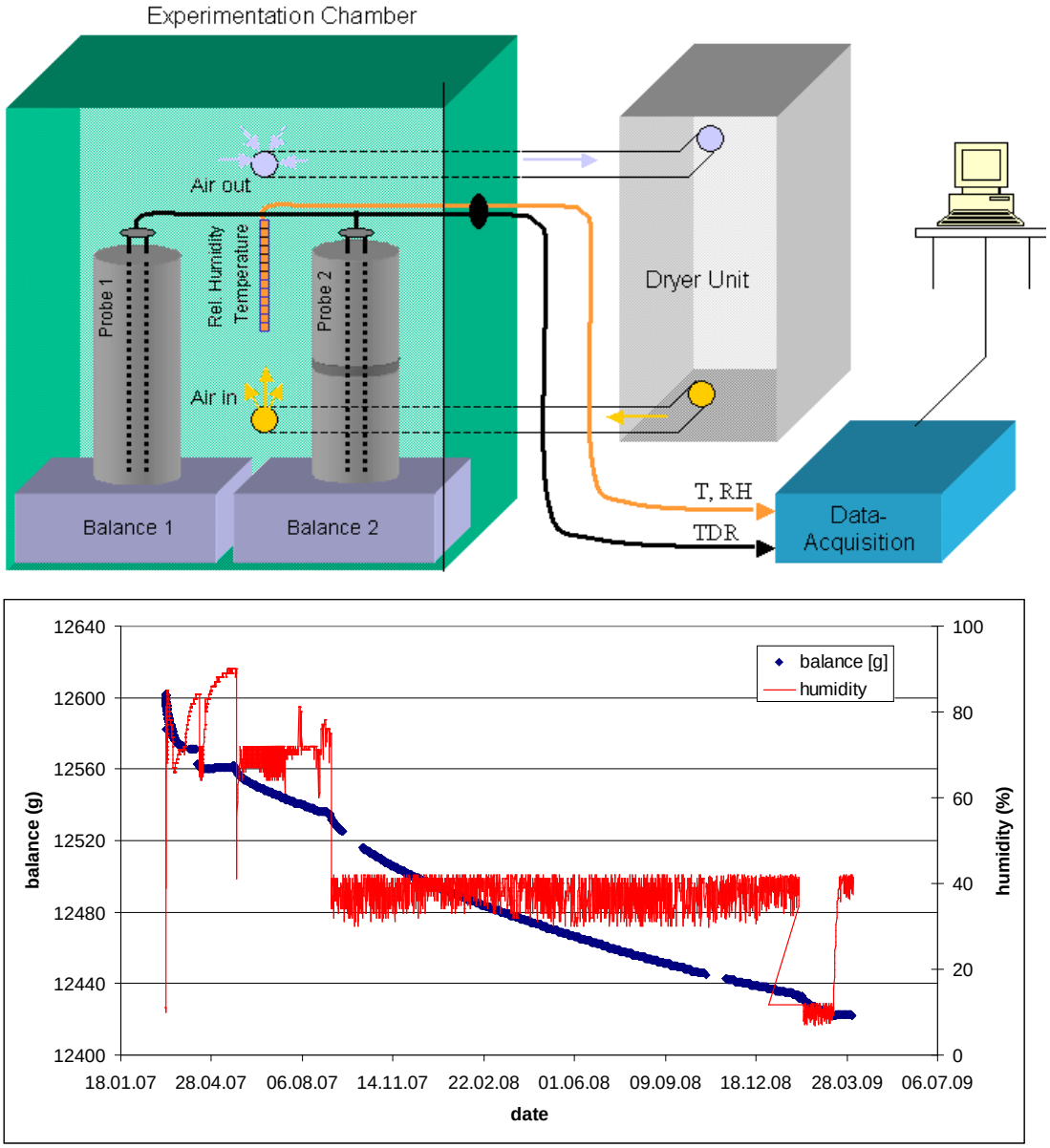

Figure 2: Example data of the long-term desaturation/resaturation experiment with an Opalinus Clay specimen from the Mont Terri URL. Humidity transients and weight measurements during an extended desaturation phase.

2.3.3 Gas permeability experiments at high gas injection pressure

Long-term gas permeability tests on Opalinus Clay core samples from the Mont Terri Underground Laboratory and from the Benken site were conducted by SCK•CEN and BGS. Both laboratories used isostatic cells, designed to match the expected in-situ stress conditions by applying an isotropic confining pressure on the test sample.

Figure 3 shows a schematic sketch of the BGS isostatic cell with the main components. The cylindrical rock specimen (diameter: 54 mm, thickness: 34 mm) is sandwiched between the end-caps and can be subject to an isotropic confining stress up to 40 MPa. The sample is jacketed in

heat-shrink Teflon to exclude confining fluid. The inlet and outlet zones for water or gas flow through the specimen are provided by porous filter discs which are recessed into the bearing surface of the end-caps. Annular guard-ring filters are recessed into the end-caps so that they completely encircle the inlet and outlet filters. Volumetric total (i.e. gas and water) flow rates for the upstream and downstream side as well as the pressure of the inlet/outlet zones and of the guard-ring filters are monitored by a data acquisition system. A more detailed description of the basic permeameter system is given in Horseman et al. (2002) and Marschall et al. (2005).

Testing was performed in an air-conditioned laboratory at a temperature of 20 ± 0.3 ºC. A typical test history comprised a sequence of test stages, namely (i) a saturation and equilibration stage, (ii) a constant rate water flow stage, (iii) a pressure recovery stage and (iv) a sequence of constant gas pressure (CP) test stages. Saturation of the specimen and constant rate water testing were accomplished with a synthetic porewater solution that matched as closely as possible the in-situ porewater chemistry (Pearson et al. 2003). This procedure was aimed at minimising osmotic flow effects and shale swelling. Helium gas was used during the gas pressure test stages.

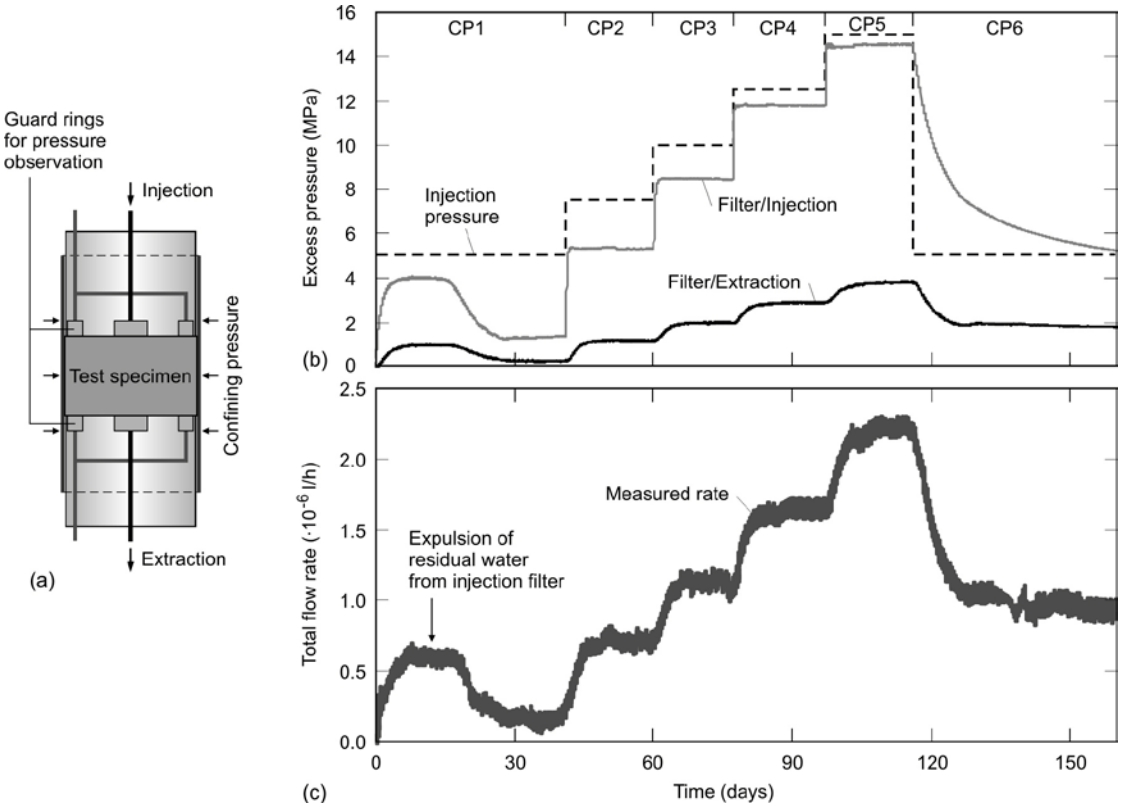

Figure 3: Gas permeability measurements on an Opalinus Clay core sample from the Benken borehole: (a) sketch of the isostatic cell containing the test specimen and (b+c) pressure and flow transients during gas testing (Marschall et al. 2005).

The water and gas permeameter tests performed by BGS were conducted with two core samples. Flow direction was parallel to bedding in one test and normal to bedding in the second. A comprehensive description of the experimental configuration and of the test procedures is given in Horseman et al. (2002).

2.3.4 Summary of laboratory testing data provided to modellers

In addition to the tests focused on gas transport described above, reports describing testing related to mechanical and hydraulic properties were also distributed to the modellers and are listed in Table 5.

Table 5: Reports on laboratory testing of the Opalinus Clay.

Reference	Testing	Data	Core source
Birchall DJ , Harrington JF, , Noy DJ, Cuss RJ. 2007. Laboratory study examining permeability evolution along an isotropic unloading stress path. BGS Open report OPEN REPORT OR/07/016. Mont Terri Project Technical Note, TN 2006-xx	Permeability during unloading under isotropic stress field.	Yes	Mont Terri BHA-5
Horseman ST, Harrington JF, Birchall DJ, Noy DJ, Cuss RJ. 2003. Hydrogeologic analyses and synthesis (HA experiment): Consolidation and rebound properties of Opalinus Clay: a long-term, fully drained test. Mont Terri Project, Technical note 2003-03	Drained consolidation, creep and rebound behaviour.	Yes	
Horseman, S.T., Harrington, J.F. (2002). Laboratory Experiments On Gas Migration In Opalinus Clay Samples From The Benken Borehole, Switzerland. Nagra Internal Report NIB 02-31	Flow of gas and water (pre/post gas test).	Yes	Benken
Laloui L, Ferrari A. 2008. Analysis of Opalinus Clay self sealing: experimental investigation (swelling tests). HA-project, Technical Note 2008-45.	Swelling tests	Yes	Mont Terri Sandy: BWS-H2 Shale: BRC1
Krooss, B., M., Alles, S. 2007. Investigation of Gas Transport Processes in the Opalinus Clay. Mont Terri Technical Note TN 2007-53	Permeability to gas and water (pre/post breakthrough). Porosimetry Deformation Tests	Yes	Mont Terri BH 4/1
Peron, H., Salager, S., Eichenberger, J, Rizzi, M., Laloui, L. 2008. HG-A Experiment: EXPERIMENTAL AND NUMERICAL ANALYSIS OF EXCAVATION DAMAGED ZONE (EDZ) ALONG TUNNELS. Mont Terri Technical Note TN 2008-54	Oedometer test WRC (drying)	No	Shale and sandy facies specimens
Laloui, L, Francois B. 2008. Benchmark on Constitutive Modelling of the Mechanical Behaviour of Opalinus Clay Focus on the Material Anisotropy. EPFL Report	Compilation of uniaxial, triaxial, oedometric and direct shear tests	No	Shale and sandy facies specimens

3 Information relating to modelling of HG-A

3.1 The HG-A Experiment

The HG-A experiment has been planned as a long-term in-situ test at the Mont Terri URL, aimed at investigating under realistic conditions the hydro-mechanical evolution of a backfilled and sealed tunnel section.

Specific objectives of the project are:

- Extension of the conceptual understanding of damage zones around cylindrical excavations (creation and long-term evolution of the EDZ)
- Determination of hydraulic conductivity of the Opalinus Clay on the tunnel scale (upscaling of hydraulic properties from borehole scale to repository scale)
- Investigation of self-sealing processes along the damage zones around backfilled tunnels
- Estimation of typical gas leakage rates from sealed tunnel sections.

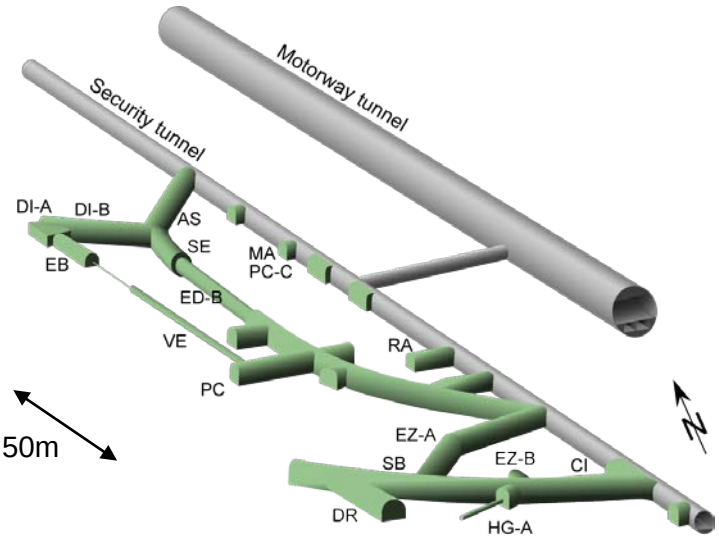

Figure 4: Schematic of Mont Terri URL showing HG-A niche and microtunnel in lower right.

The HG-A experiment is located in a niche off Gallery 04 as shown in Figure 4. The HG-A microtunnel is oriented parallel to the strike of the bedding planes in the Opalinus at that location. In this area of the URL, the shaly facies are composed of marly shales with numerous lenses of grey/white sandy limestones and weakly cemented fine-grained brownish siderite layers.

The experiment has been planned in 6 phases: (i) the excavation of a microtunnel and monitoring of key geotechnical parameters during the open tunnel phase, (ii) backfilling and sealing of the tunnel with a large-size hydraulic packer system (diameter: 940 mm, sealing length: 3000 mm, as shown in Figure 5), (iii) artificial resaturation of the sealed tunnel section, (iv) a series of long-term water injection tests for determining the hydraulic conductivity of the rock on the tunnel scale, (v) gas injection tests and, finally, (vi) the dismantling of the test site. Currently the project is at the end of phase iv, preparing for the start of phase v (gas injection tests).

A simplified view (not all boreholes shown) of the HG-A experimental layout is shown in Figure 5. The drilling of the pilot borehole and microtunnel is described in Meier et al (2005). The microtunnel is divided into three main sections

0-6m Liner section: Open tunnel section with steel liner

6-10m Packer/sealing section: Megapacker and grouted seal zone

10-13m Test zone: Instrumented section that will be used for testing and gas injection.

The test zone is equipped with injection lines, piezometers, strain gauges, extensometers, TDRs and geophones. The completion and instrumentation of the test zone is described in Trick & Roesli (2007).

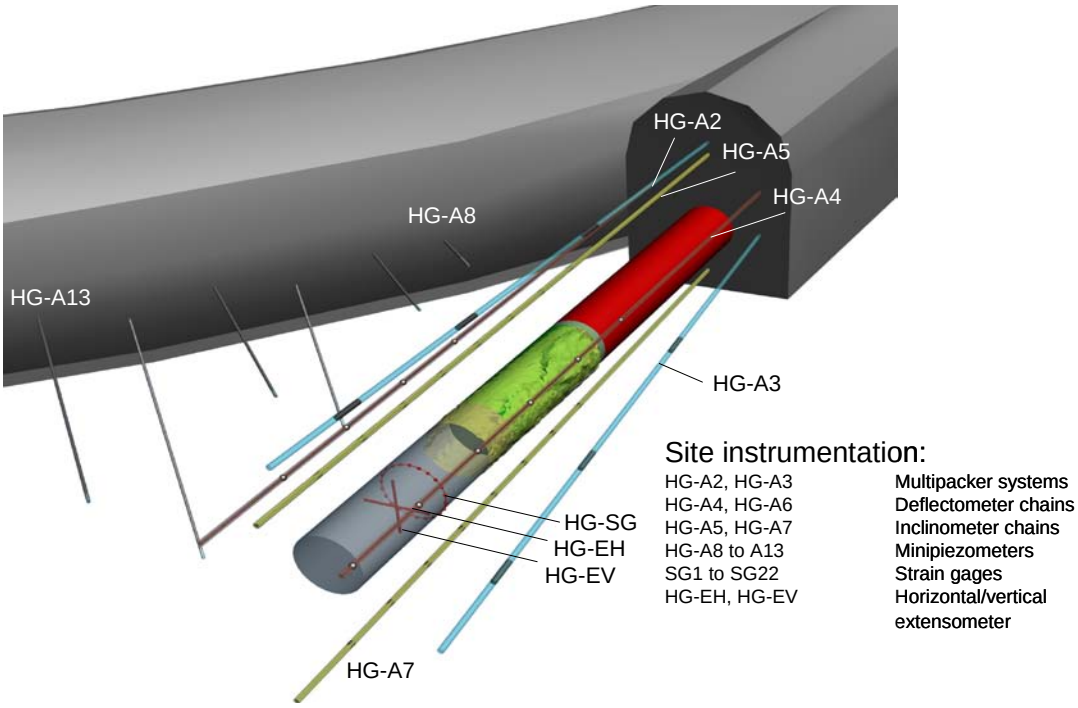

Figure 5: HG-A experiment layout at Mont Terri prior to drilling of BHG-A14-BHG-A25

3.2 Experimental procedure

After the test section had been instrumented, it was backfilled on 05/05/06. The megapacker was emplaced on 30/06/06 and the gap between the packer and test section was then sealed. After sealing the megapacker was inflated on 24/10/06 and test section saturation started on 21/11/06.

From 21/11/06 until 13/07/07 a series of saturation/injection system performance tests were performed. The system was then left to recover for over 2 months prior to restarting injection tests on 26/09/07. After the initial resaturation, injection rates declined from ~15 ml/min in October 2007 to 1.5 ml/min in January 2008.

An extended multi-rate water injection test 0108RILIQ was initiated on 23/01/08 and is ongoing. During the test, injection rate and megapacker pressure have been controlled to investigate the hydromechanical response to water injection at different seal zone effective stresses.

Time histories of packer, test and seal zone pressure together with injection rate are shown in Figure 6.

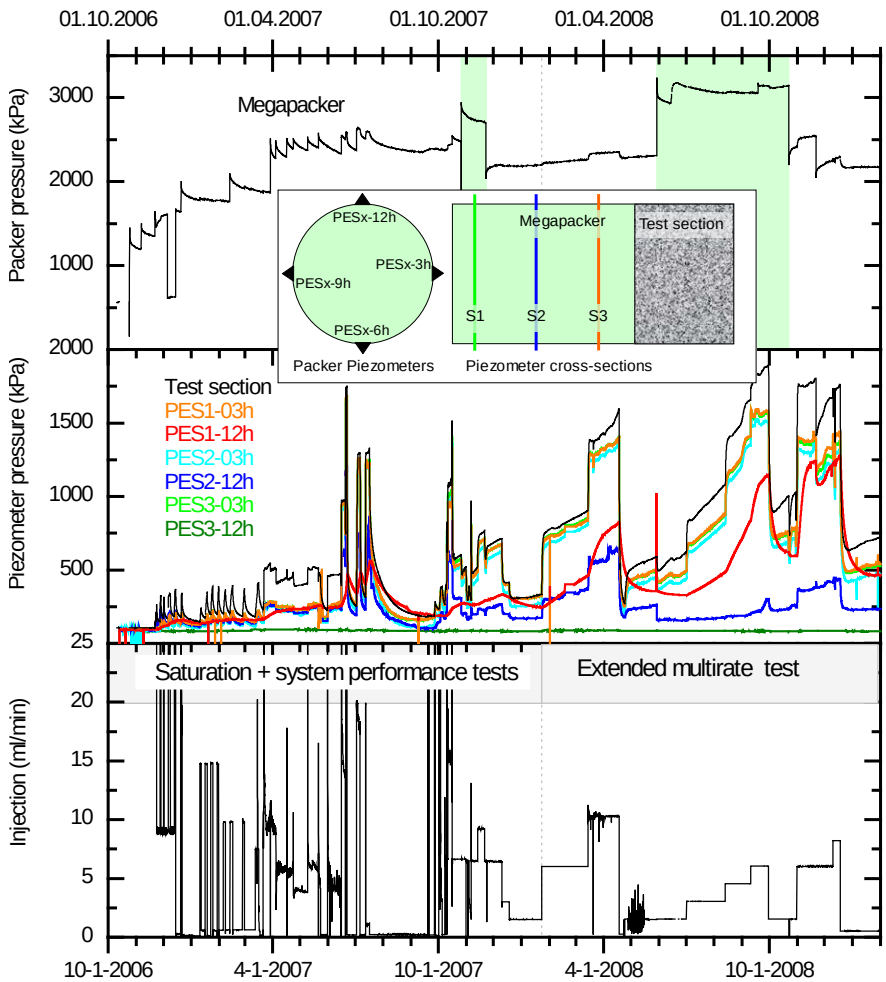

Figure 6: Megapacker, test and seal zone pressure from the start of saturation to end of January 2009.

3.3 The stress state around the HG-A site

No pre-excavation stress measurements were performed at the site. Two Geokon Biaxial stressmeters were installed on 13/10/05 about 8 months after excavation of the microtunnel. These sensors include 3 vibrating wire sensors within a thick-walled cylinder in the plane normal to the borehole axi. The biaxial stress field can be estimated assuming a homogeneous isotropic elastic material. The calculated stresses from the isotropic model were very low. A study by Corkum & Martin (2008) considered the possible response in the anisotropic Opalinus. Corkum & Martin (ibid) concluded that "by not accounting for anisotropic stiffness, the closed-form solution calculates stresses that are significantly in error — a difference of up to 70% for the conditions explored in the modelling study."

The analysis also suggested that although a numerical calibration method was developed, field-verification or further numerical studies were required to build confidence in the approach. Analysis of the models did however suggest that the instruments were typically more sensitive to changes in differential stress (σ_1-σ_2) than mean stress (σ_1+σ_2).

The proximity of the microtunnel to Gallery 04 (see Figure 7) and the influence of the enlarged niche area suggest that stresses around the microtunnel will be affected by the larger excavations (especially close to the start of the tunnel). The seal zone is over 5m (1 tunnel diameter) from the wall of Gallery 04 suggesting that stresses should be approaching the undisturbed values.

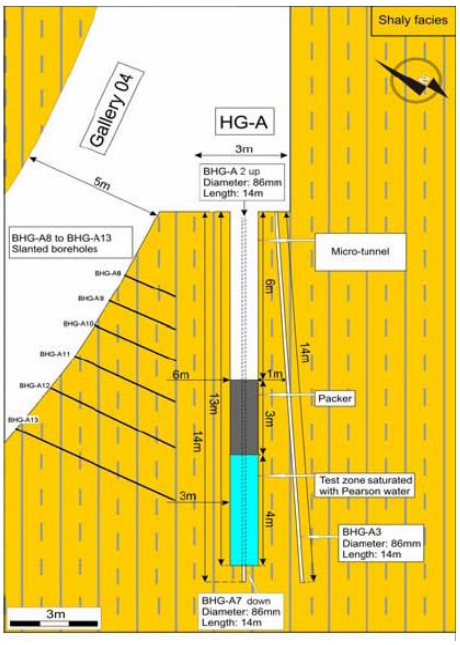

Figure 7 Layout of microtunnel and nearby excavations.

The microtunnel runs at 238.5° relative to grid North such that the minimum stress (as suggested by Martin&Lanyon 2003a) runs along the tunnel axis. Previous FLAC3D modelling by Vietor used a simplified version of the Bossart & Wermeille (2003) tensor as boundary conditions (see Figure 8).

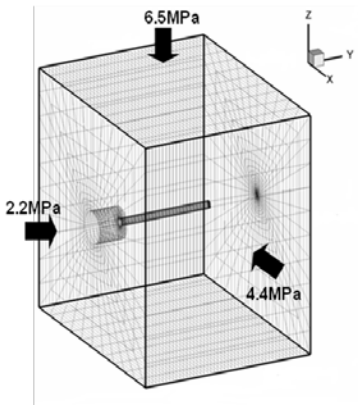

Figure 8: Layout of microtunnel FLAC3D model of Vietor.

Options for calibration/consistency checks on stress field

The laboratory scale stress tensor is uncertain as is the appropriate tensor to use for “far-field” boundary conditions at HG-A. The pore pressure and deformation response to excavation of the microtunnel was monitored and the overall pattern of response (e.g. for pore pressure

regions of compression vs dilation) should provide some control on the local stress field (initial calculations have been performed by EDF as reported at the November meeting in Wettingen)

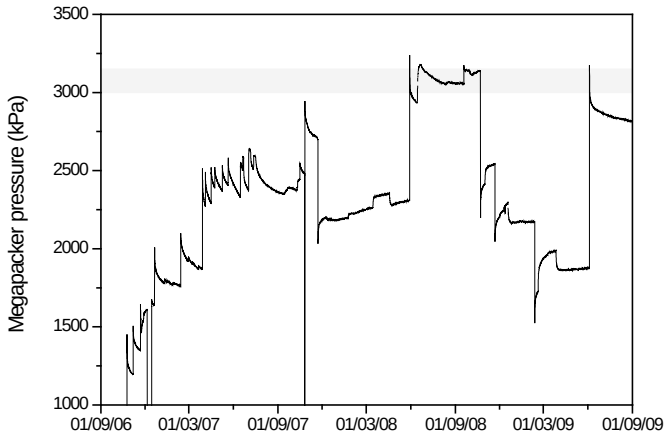

Figure 9 Megapacker pressure from installation to 01/09/09.

The maximum pressure achieved during inflation of the Megapacker was approximately 3200 kPa as shown in Figure 9 and the observed response to inflation may also be useful in limiting the possible range of stresses.

4 Information related to modelling HG-C

Packer tests in boreholes have been the main source of field data contributing to the characterisation of gas transport properties in the Opalinus Clay (Croisé et al. 2006). The general test procedure comprises a combination of hydrotest, gas injection and pressure recovery sequences.

A typical test configuration consists of a short straddle double packer system as shown in Figure 10. After packer inflation, the hydrotest sequence is started. The purpose of this sequence is a comprehensive hydraulic characterisation of the formation with particular emphasis on flow model identification and estimation of hydraulic conductivity, storage coefficient and hydraulic head. At the end of the hydraulic test sequence, when the interval pressure has recovered towards the static formation pressure, the fluid in the test interval is replaced by gas. The subsequent gas injection phase may be implemented as an event at constant flow rate ("gas threshold pressure test") or as a multi-step constant head event. The final stage of gas testing is a shut-in followed by a long-term pressure recovery phase.

The primary purpose of the gas test sequence is the determination of the gas entry pressure of the formation. If the test is designed to comprise an extended gas injection phase, further gas transport properties can be estimated, such as the shape factors of the capillary pressure and relative permeability relationships. At Mont Terri, gas injection experiments were complemented by hydraulic and geomechanical crosshole observations, intended to investigate coupled hydromechanical processes in the vicinity of the injection borehole.

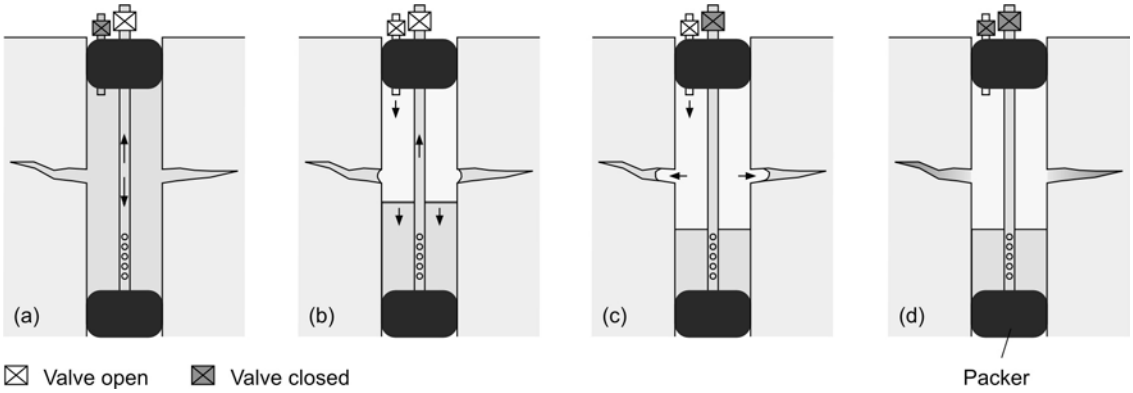

Figure 10: Gas threshold pressure testing in boreholes - test configuration and procedure: (a) hydrotest sequence, (b) water / gas displacement DISP, (c) gas injection phase GRI and (d) gas pressure recovery phase GRIS.

Comprehensive in-situ gas experiments were conducted at Mont Terri at the HG-C site and in other sites (Marschall et al. 2005, Croisé et al. 2006). The experiments include conventional gas threshold pressure tests, hydro-frac tests, long-term water injection tests at elevated water injection pressure and long-term gas injection tests at elevated gas injection pressure.

4.1 Experimental procedures

The HG-C experiment at Mont Terri URL was set up to investigate gas migration mechanisms at different gas pressures ranging from below pore water pressure to high pressures leading to dilatancy-controlled gas flow. The experiment is being performed in four highly instrumented boreholes of the GP-A/GS site at the Mont Terri Underground Laboratory. The boreholes were drilled inclined with respect to the tunnel floor, but perpendicular to bedding planes present in the formation. Figure 11 shows the layout of the tunnel and the four boreholes.

4.1.1 The GS/GPA experiments

Boreholes GS-1 and GS-2 were instrumented for accurate recording of pressures (triple packer systems). Boreholes GS-3 and GS-4 were instrumented for recording displacements (fixed installed micrometers). Water and gas injection tests were conducted in zone 2 of borehole GS-2. Full details are presented in Enachescu et al (2000a-e). The detailed objectives of the tests were (Enachescu et al 2002):

- Describe formation parameters under undisturbed conditions by testing the formation with water and gas. Derive transmissivity, static formation pressure, gas threshold pressure, flow geometry.
- Starting from GS-2 Zone 2, create a hydro-frac along a bedding plane that would intersect the middle intervals (Zone 2) in GS1, 3 and eventually 4. Derive frac pressure and reopening pressure.
- Test the formation after the frac with water and gas and compare results with undisturbed formation. Conduct test phases at different pressure levels, to derive transmissivity-pressure dependency.
- Monitor and evaluate interference responses in borehole GS-1.
- Measure rock deformation using FIMs installed in boreholes GS-3 and GS-4, and correlate measurements with pressure observed in GS-2.
- Repeat water and gas tests after a long lasting re-hydration phase to characterise fracture self sealing behaviour in the Opalinus clay.

The complete experimental sequence included the following 8 phases as listed in Table 6.

Table 6: Overview of GS experimental phases at HG-C site.

Test Phase	Method	Aim
Hydro-1	Pulse and constant head rate tests using synthetic porewater	Characterisation of hydraulic behaviour of the undisturbed formation
Gas 1	Stepwise increasing gas pressure test	Calculation of the gas threshold pressure and gas mobility of the undisturbed formation
Frac	Hydrofracture test	Propagate a fracture from GS-2 to intersect Zone 2 of the other three boreholes
Hydro-2	Stepwise increasing pressure pulse test with synthetic porewater	Characterisation of the pressure-transmissivity relationship after the hydro-frac.
Gas-2	Nitrogen gas pulse injection	Characterisation of the ability of the formation to transport gas after the hydro-frac
Gas-3	Constant rate nitrogen gas injection	Confirm the formation behaviour observed during the Gas 2 phase and create a high gas saturation along the fracture plain.
Hydro-3	Resaturation and constant head tests with synthetic porewater	Long-term re-hydration of the fracture plane and the determination of the system transmissivity after fracture self-sealing.
Gas-4	Constant rate nitrogen gas injection	Derive the gas mobility and geometry of gas flow after a long term fracture self-sealing process.

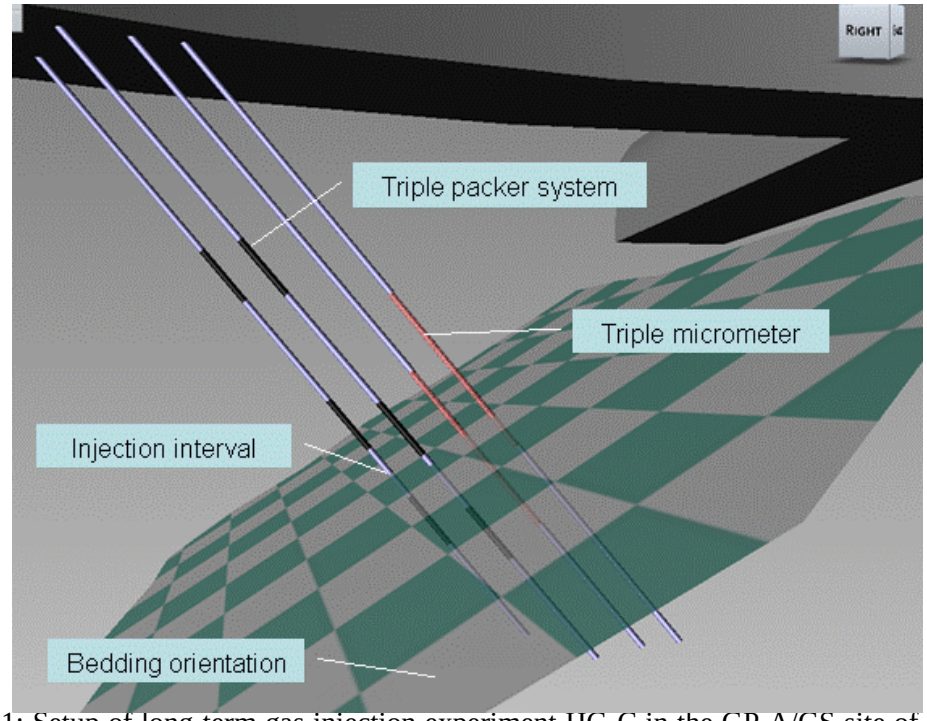

Figure 11: Setup of long-term gas injection experiment HG-C in the GP-A/GS site of the Mont Terri Rock Laboratory. The test configuration consisted of four boreholes.: Two boreholes are equipped with triple packer systems, and the other two with fixed installed micrometers.

4.1.2 The HG-C experiment

Further tests were initiated in 2006 in the first phase of the HG-C experiment (Mont Terri Phase 12). Multi-step water/gas injection experiments were performed in 2007 and 2008 at the test site, using water and gas injection pressures up to 60 bars. The experiments aimed at determining stress-dependency of water and gas transfer.

The long-term monitoring data include injection rates, interval pressures rates and axial deformation, acquired in the 4 boreholes of the site. Figure 12 shows the time series of a long-term hydraulic test and a gas injection test.

4.1.3 The HG-D experiment

A fifth borehole HG-D1 has been drilled as part of a new project (HG-D) to extend the HG-C experiment. The new borehole has been cored, logged and imaged and a triple packer system has been installed. Gas permeability tests will be performed on core specimens. Hydraulic tests are planned and gas injection tests with non-reactive and reactive tracer gases will be conducted in the new borehole. Databases may be delivered to form a new prediction/evaluation exercise.

The HG-C/D experiment was selected as an exercise for integrated system validation. Comprehensive data bases are available, comprising:

- Long-term and multi-step hydraulic test;
- Long-term and multi-step gas injection tests.

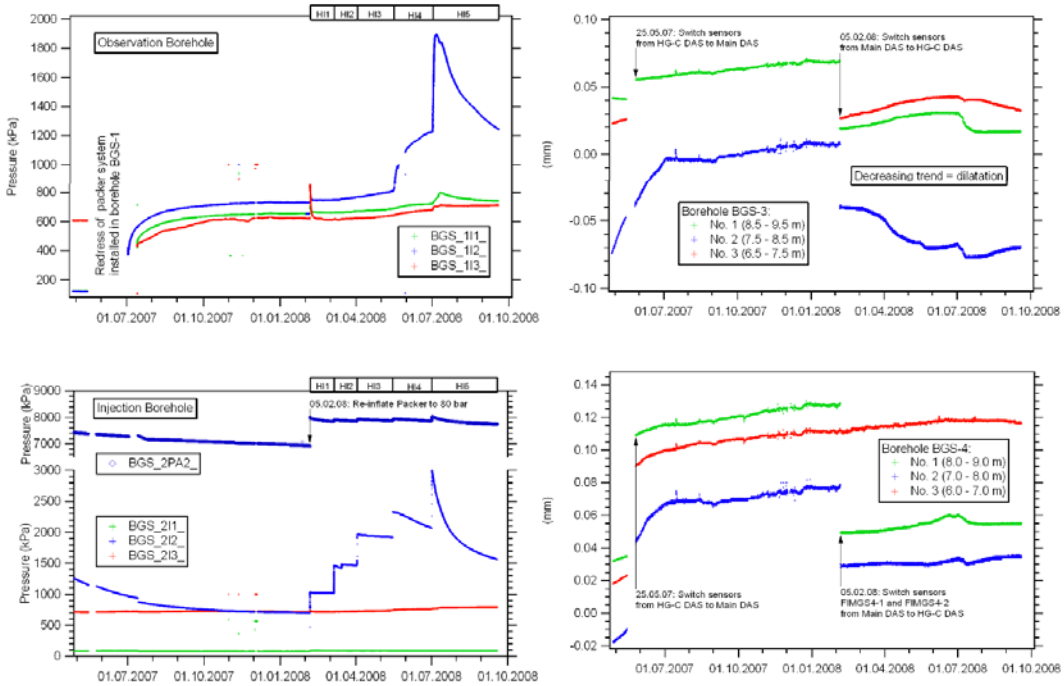

Figure 12: Long-term gas injection experiment in the HG-C site: interval pressure and injection rate in the triple packer systems of boreholes BGS1 and 2 (left side) and axial deformation in boreholes BGS3 and BGS-4 .

References

Birchall DJ , Harrington JF, , Noy DJ, Cuss RJ. (2007). Laboratory study examining permeability evolution along an isotropic unloading stress path. BGS Open report OPEN REPORT OR/07/016. Mont Terri Project Technical Note, TN 2006-xx

Bock, H. (2000). RA experiment - Rock mechanics analyses and synthesis: Data report on rock mechanics. Mont Terri Technical Report TR 2000-02.

Bossart, P. and Wermeille, S. (2003). The Stress Field in the Mont Terri Region – Data Compilation. -Report of the FOWG, Geology Series, N°4, pp 65-92.

Corkum, A. G., Martin, C. D. Martin. (2007). Modelling a Mine-by Test at the Mont Terri Rock Laboratory, Switzerland. Int. J. Rock Mech. Min. Sci., 44, 846-85.

Corkum, A. G., Martin, C. D. (2008). HG-A/Phase 13 Experiment: Evaluation of biaxial stressmeters. Itasca Technical Memorandum ICG08-2509-19TMD.

Croisé, J., Mayer, G., Marschall, P., Matray, J.M., Tanaka, T., Vogel, P. (2006). Gas Threshold Pressure Test Performed at the Mont Terri Rock Laboratory (Switzerland): Experimental Data and Data Analysis. Oil & Gas Science and Technology - Rev. IFP, Vol. 61 (2006), No. 5, pp. 631-645 DOI: 10.2516/ogst:2006003

Daneshy, A., Blümling, P., Marschall, P., Zuidema, P. (2004). Interpretation of Field Experiments and Observation of Fracturing Process. SPE 86486 presented at the SPE International Symposium and Exhibition on Formation Damage Control held in Lafayette, Louisiana, U.S.A., 18–20 February 2004.

Enachescu, C., Jäggi, K., Schmid, A., Wozniewicz, J. (2000a). Mont Terri - Phase V / GP-A Pre-frac hydraulic and gas longterm tests in borehole BGS-2: Data acquisition and analysis report. Mont Terri Technical Note TN 2000-07.

Enachescu, C., Jäggi, K., Schmid, A. & Wozniewicz, J. (2000b). GP-A Experiment: Pre-frac hydraulic and gas long-term tests in borehole BGS-2. Mont Terri Technical Note TN 2000-007.

Enachescu, C., Jäggi, K., Schmid, A. & Steffen, P. (2000c). GP-A and GS Experiments; Report on Hydraulic Long Term Testing (water and gas) in Boreholes BGS-2 (active) and BGS-1 (observation) Mont Terri Technical Note TN 2000-008.

Enachescu, C., Jäggi, K., Schmid, A. & Steffen, P. (2000d). GS – Hydraulic and gas long-term tests after hydraulic fracturing – Analysis report. Mont Terri Technical Note TN 2000-009.

Enachescu, C., Jäggi, K., Pine, R.J. & Schmid, A. (2000e). GS - Hydraulic fracturing in borehole BGS2. Mont Terri Technical Note TN 2000-010.

Enachescu, C., Blümling, P., Castelao, A., Steffen P., (2002). Mont Terri GP-A and GS Experiments Synthesis Report. Nagra Internal Report NIB 02-51.

Horseman, S.T., Harrington, J.F., Noy, D.J., (2002). Laboratory Experiments On Gas Migration In Opalinus Clay Samples From The Benken Borehole, Switzerland. Nagra Internal Report NIB 02-31. Nagra, Wettingen, Switzerland.

Horseman, S.T., Harrington, J.F., Birchall, D.J., Noy, D.J., Cuss, R.J. (2003). Hydrogeologic analyses and synthesis (HA experiment): Consolidation and rebound properties of Opalinus Clay: a long-term, fullydrained test. Mont Terri Project, Technical note 2003-03

Horseman, S.T., Harrington, J.F. (2002). Laboratory Experiments On Gas Migration In Opalinus Clay Samples From The Benken Borehole, Switzerland. Nagra Internal Report NIB 02-31

Krooss, B., M., Alles, S. (2007). Investigation of Gas Transport Processes in the Opalinus Clay. Mont Terri Technical Note TN 2007-53

Laloui L, Ferrari A. (2008. Analysis of Opalinus Clay self sealing: experimental investigation (swelling tests). HA-project, Technical Note 2008-45.

Laloui, L, Francois B. 2008. Benchmark on Constitutive Modelling of the Mechanical Behaviour of Opalinus Clay Focus on the Material Anisotropy. EPFL Report

Lanyon, G.W., Marschall, P., T. Trick, de La Vaissière, R., Shao, H., Leung, H. (2009). Hydromechanical Evolution and Self-Sealing of Damage Zones around a Microtunnel in a Claystone Formation of the Swiss Jura Mountains. ARMA 2009, Ashville, North Carolina , in press.

Marschall, P., Croisé, J., Schlickenrieder, L., Boisson, J.-Y., Vogel, P., Yamamoto, S. (2004): Synthesis of Hydrogeological Investigations at the Mont Terri Site (Phases 1 to 5). - Heitzmann, P. ed. 2004: Mont Terri Project- Hydrogeological Synthesis, Osmotic Flow. Reports of the Federal Office for Water and Geology, FOWG, Geology Series No. 6.

Marschall, P., Horseman, S., Gimmi,T. (2005). Characterisation of gas transport properties of the Opalinus Clay, a potential host rock formation for radioactive waste disposal. Oil and Gas Technology Revue de l'Institut Français du Pétrole, 60, No. 1&2.

Marschall, P., M. Distinguin, H. Shao, P. Bossart, C. Enachescu & T. Trick. (2006). Creation and Evolution of Damage Zones Around a Microtunnel in a Claystone Formation of the Swiss Jura Mountains. SPE Paper 98537.

Marschall, P., T. Trick, G.W. Lanyon, J. Delay and H. Shao. (2008). Hydro-Mechanical Evolution of Damaged Zones around a Microtunnel in a Claystone Formation of the Swiss Jura Mountains. ARMA 2008, San Francisco.

Martin, C.D., Lanyon, G.W. (2003a). EDZ in clay shale: Mont Terri. Mont Terri Techn.Rep.2001, 1. With contributions from P. Bossart and P. Blümling.

Martin, C.D., Lanyon, G.W. (2003b). Measurement of in-situ stress in weak rocks at Mont Terri Rock Laboratory, Switzerland. International Journal of Rock Mechanics and Mining Sciences, 40(7-8), 1077-1088.

Meier, O., Nussbaum, C., Bossart, P. (2005). HG-A experiment: Drilling of the microtunnel (BHG-A0 and BHG-A1). Mont Terri Technical Note TN 2005-055.

Nagra (2002) Projekt Opalinuston: Synthese der geowissenschaftlichen. Untersuchungsergebnisse Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle. Nagra NTB 02-03.

Peron, H., Salager, S., Eichenberger, J, Rizzi, M., Laloui, L. (2008). HG-A Experiment: experimental and numerical analysis of Excavation Damaged Zone (EDZ) along tunnels. Mont Terri Technical Note TN 2008-54

Pearson, F.J., Arcos, D., Bath, A., Boisson, J.-Y., Fernández, A.M., Gaebler, H.E., Gaucher, E., Gautschi, A., Griffault, L., Hernan, P. and Waber, H.N. (2003). Geochemistry of water in the Opalinus Clay formation at the Mont Terri Rock Laboratory – Synthesis Report. Bern, Switzerland, Berichte des Bundesamtes für Geologie und Wasser – Serie Geologie, Nr. 30.

Trick, T, Roesli, U. (2007). Mont Terri Project HGA- Experiment (Gas path through host rock and along seals): Test and sealing zone instrumentation As-built report. Mont Terri Technical Note TN 2006-039.

Wermeille, S., Bossart, P. (1999) In-situ stresses in the Mont Terri region - data compilation. Tech. Rep., Swiss National Hydrological Survey.

Appendix A Description of HG-A Data Delivery

A.1 HG-A Coordinate system

Currently two coordinate systems are being used:

- Swiss UTM/masl coordinates for boreholes and tunnels;
- Local coordinates relative to microtunnel for instruments in the test and seal sections.

These two systems are linked but a single local coordinate system that can be used for both geosphere and microtunnel sensors is preferable. Sensor positions in the field can be measured as previously and can then be converted into the local modelling coordinate system.

A.1.2 Local coordinate system for data and modelling

The following coordinate system is suggested:

- Origin at the centre of the mouth of the microtunnel;
- Y-axis horizontal positive running along the microtunnel centre;
- X axis horizontal positive at 90° to the Y axis;
- Z axis vertical upwards.

In this coordinate system bedding dips towards negative X direction and strikes roughly along the Y axis. The mouth of the microtunnel is at 579407.941, 247546.129, 512.983 in UTM/masl coordinates. The microtunnel runs at 238.5° relative to grid North as shown in Figure A.1.

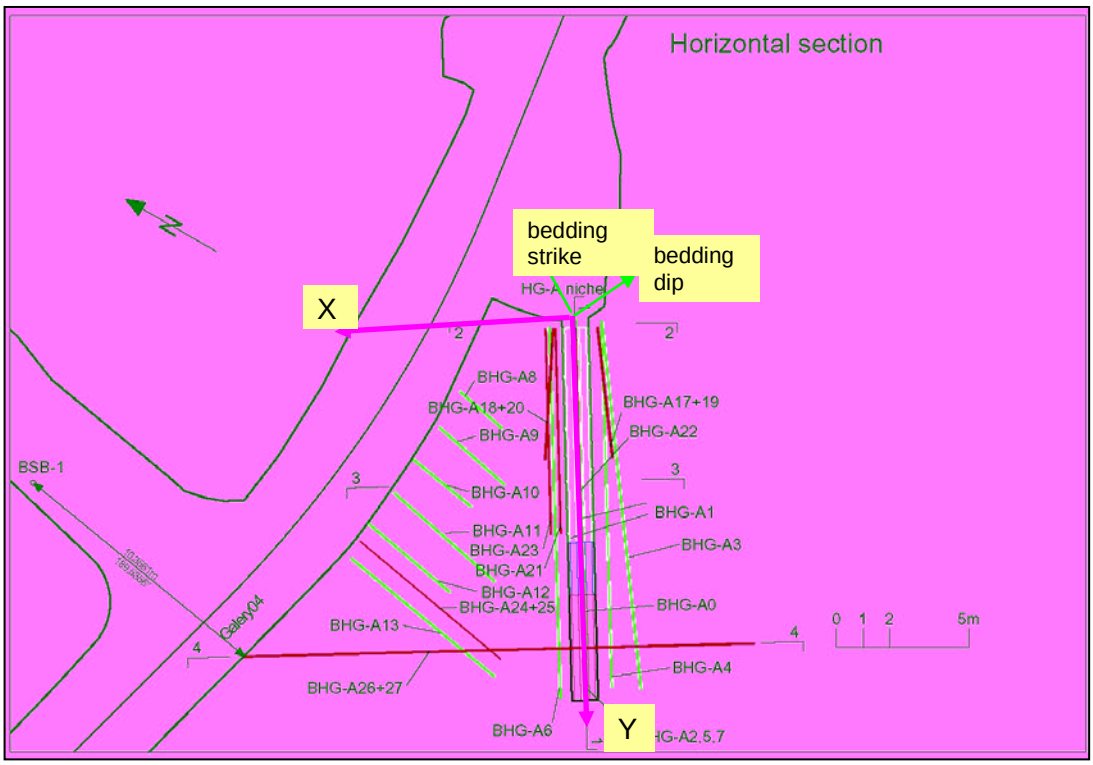

Figure A.1: Suggested modelling local coordinate system.

A.1.2 Conversion to local coordinate system

The UTM locations of borehole starts and ends are available and positions along the borehole can be estimated using linear interpolation. The UTM positions can then be converted to local coordinates using the following transformation:

$$
\begin{aligned}
X_{Local} &= -0.522\left(X_{UTM} - 579407.941\right) - 0.853\left(Y_{UTM} - 247546.129\right) \\
Y_{Local} &= 0.853\left(X_{UTM} - 579407.941\right) - 0.522\left(Y_{UTM} - 247546.129\right) \qquad (1) \\
Z_{Local} &= Z_{UTM} - 512.983
\end{aligned}
$$

Position along the axis of the microtunnel can be estimated from the pilot hole survey (BHG-A00). The local coordinates along the axis can therefore be calculated in a similar manner using equation 1. Coordinates of sensors on the microtunnel wall can be estimated assuming a 1.035m diameter cylinder oriented along the local Y axis (238.5° relative to Swiss grid coordinates). In general locations have been specified as “clock positions” (as shown in Figure A.2) on the microtunnel wall and these can be converted to local coordinates according to the equations:

$$
\begin{aligned}
X_{wall} &= X_{axis} + 0.5175 \times \sin\theta \\
Y_{wall} &= Y_{axis} \qquad (2) \\
Z_{wall} &= Z_{axis} + 0.5175 \times \cos\theta
\end{aligned}
$$

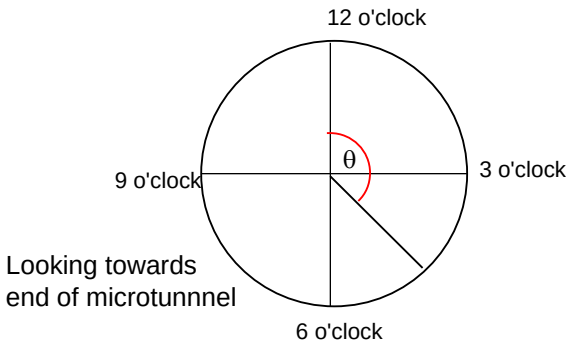

Figure A.2: Clock positions in microtunnel.

More detailed surveys of the microtunnel surface are available but this simplified method of estimating instrument locations should be sufficient for most analyses.

A.2 Sensors and measurements

In order to simplify presentation of the data to outside groups a revised sensor naming convention is suggested. The convention is based on that used by Solexperts for the GMT project and separates the instruments into two groups: those located in boreholes and those located in the microtunnel.

Sensors in boreholes are named **B**-*HHHINXX* where *HHH* is the borehole name (e.g. A02) *IN* is the instrument type (e.g. PI for internal piezometer) and *XXX* is an identifier (usually indicating location e.g. 1 for interval 1).

Those in the microtunnel are **M**-*INXXXXX* where *IN* is the instrument type (e.g. PI for internal piezometer) and *XXX* is an identifier (usually indicating location e.g. S1-3h for 3 o'clock in section 1). The different sensor types (IN) are listed below in Table A.1.

Table A.1: Sensor types, units and number of sensors.

IN	**Sensor type**	**Unit**	**Total**	**Bore-holes**	**Micro-tunnel**
DE	Clinochain	mm/m	16	16	
DX	Deflectometer – horizontal	mm/segment	9	9	
DY	Deflectometer – vertical	mm/segment	9	9	
EH	Extensometer – horizontal	mm	1		1
EV	Extensometer – horizontal	mm	1		1
Fl	Flow meter	ml/min	1		1
PA	Packer pressure	kPa	8	6	2
PE	Piezometer – external	kPa	28	14	14
PI	Piezometer – internal	kPa	0	0	
PS	Stress meter	kPa	6	3	
PT	Stress meter temperature	°C	3	3	
RH	Relative humidity	%	2		2
RT	Temperature	°C	2		2
SG	Strain gauge	µstrain	22		22
ST	Strain gauge temperature	°C	22		22
TP	Total pressure	kPa	6		6
TDR	Time Domain Reflectometer	Ns	10		10

A2.2 Pore pressure and stress

Pore pressures are currently reported as either bar or kPa by Solexperts and converted to kPa. The values are absolute as measured at the gauge (typically located in the niche). In the future it would be useful to account for gauge height. As we are interested in both gas and water pressure it is suggested that the pressure data is corrected to the sensor elevation and reported in kPa absolute.

1) $$P_{model} = P_{measure} + \rho g \times (Z_{sensor} - Z_{gauge})$$

Where $P_{measure}$ is the measured absolute pressure at the gauge in kPa, Z_{sensor} is the elevation of the sensor, Z_{gauge} is the elevation of the gauge, ρ is the density of fluid in the line between the gauge and the sensor and g is the acceleration due to gravity (9.81 m/s^2). The nature of any piezometer filters needs to be clarified to address concerns about whether air or water pressure is measured. Stresses should also be reported in kPa for consistency.

A2.2 TDRs

Data handling for the TDRs is not finalised as yet. TDR Reflectograms have been acquired and preliminary analyses performed by Franz Königer from the Forschungszentrum Karlsruhe to estimate two-way travel time and volumetric water content. Many of the TDRs are located at the microtunnel wall and so are affected by the permittivity of both the rock and the packer or tunnel fill.

A2.3 Temperature

Temperature is currently reported as °C and temperature measurements are largely supporting measurements for accurate calibration of other sensors. It is not expected that there will be significant temperature transients during the experiment. Analysis of temperature data for purposes other than sensor calibration can probably focus on changes in temperature rather than absolute values.

A.2.4 Flow measurements

Currently only the injection flow into the test section has been measured. In later phases of HG-A it may be necessary to measure injections of gas and any outflows that can be captured. Flows should be either in ml/min (for water) or as mg/s mass flow for gas.

A.2.5 Strains and deformations

Strains are currently measured in µstrain while deformations are measured as either: mm, mm/segment or mm/metre according to the measurement method. These units are suitable for analysis and there is no need for any conversion.

The clinochains measure the inclination in mm/m. A positive change in inclination indicates an increase in inclination, a negative change a decrease in inclination

The chain deflectometer heads measure the deflections in mm. The average over the first 50 values was calculated and chosen as zero measurement. The x-component is vertically installed, the y-component horizontally. Looking towards the end of the borehole (from the HG-A niche), a positive change in x-deflection indicates an upward movement; a positive change in y deflection indicates a movement towards the left side (9 o-clock in Figure A.2). To calculate the total change in the boreholes according to the chain-deflectometers, the deflection should be calculated into vertical and horizontal movement over the whole borehole.

A.2.5 Borehole stressmeters

The borehole stressmeter is discussed in a separate note including an analysis by Itasca of the influence of the expected material heterogeneity. Each stressmeter includes 3 vibrating wire sensors (at 60° intervals) measuring deformation. These deformations can be used to estimate the biaxial stress –field in an isotropic medium as described within the Geokon manual (provided in data package).

An investigation of the influence of the expected anisotropy of the Opalinus was performed by Itasca and is documented within a short report. As an output of the Itasca work a material specific (in terms of anisotropic elastic properties) calibration was derived.

The estimated biaxial stresses are therefore given for both the isotropic and anisotropic models together with the 3 deformations in the Stressmeter spreadsheet.

A.3 Contents of Data Package 1

The spreadsheets containing measured data, sensor positions and a summary log of activities are listed below.

Table A.2: Spreadsheets in Data Package 1

File	**Content**
ValEXcavationEDF 090909.xls	Sensor data (excluding stressmeter) resampled to 1/hour
ValEXcavationEDF stressmeters 090909.xls	Stressmeter data resampled to 1/hour
HG-A Sensors FORGE V0.xls	Sensor positions, types, borehole surveys
instrument install.xls	Timetable of excavation and installation of sensors around microtunnel

A.4 Supporting documents

All Mont Terri Technical Notes and other documents from the Mont Terri Consortium are provided in confidence for the sole purpose of modelling the HG-A experiment within the FORGE Project.

Table A.3: Supporting Mont Terri documents in Data Package 1

Data Acquisition logs	
HGA-Data Trend Report-1 No plots.pdf	Plots and events 01/01/05-30/09/05
HGA-Data Trend Report-2_complete_.pdf	Plots and events 01/10/05-31/12/05
Microtunnel drilling, mapping and instrumentation	
TN2005_55 Drilling of the microtunnel.pdf	Drilling and installation of liner
TN2005_28 Microtunnel and borehole survey and observations.pdf	Surveys of microtunnel and boreholes
TN2005-49 Microtunnel structural mapping March 2005.pdf	Mapping after excavation
TN2006_31 Microtunnel breakout mapping February 2006.pdf	Repeat mapping after 11 months
TN 2006-01 strain gauge and extensometer.pdf	Strain gauge/extensometer installation

Borehole sensor installation and calibration reports		
Boreholes	**File**	**Contents**
All	Gas pathway instrumentation.pdf	ASCE paper on HG-A instrumentation and initial responses
A2,A3,A8,A9,A10,	SN-Borehole Completion Report 1	Borehole completion

A11,A12,A13	_Hydrogeology_-Final.pdf	
A24,A25	SN-Borehole Completion Report 2 _Hydrogeology_-Final.pdf	Borehole completion
A2	QLR-HW1 in BHG-A2i1 May 2005.pdf	Hydraulic testing in A2 May 2005
A4,A6 (deflectometer) A5,A7 (clino-chain)	TN 2005-05 Deflectometer installation.pdf	Installation and calibration of deflectometers and clino chains
A4,A6	geo_chain_deflec_en/fr.pdf	Solexperts info on Deflectometers
A5,A7	geo_clino_en/fr.pdf	Solexperts info on Clinochain
A21,A22,A23	4350BX Biaxial Stressmeter (REV C).pdf	Geokon stressmeter manual
A21,A22,A23	SN-Borehole Completion Report - Stressmeter.pdf	Installation and calibration of borehole stressmeters
A21,A22,A23	Itasca Stressmeter Note 200908.pdf	Analysis by Itasca of stressmeter response in anisotropic medium

Appendix B Description of HG-C Data Delivery

B.1 GS/GPA Experiment

The GS/GPA experiments were performed in the four boreholes BGS1-4. The experimental sequence is summarised in Table B.1 (from Enachescu et al.2002).

Table B.1: Test phases in GS/GPA experiment.

Start	End	Test Phase	Comment
25/11/99 12:40	01/02/00 10:10	Hydro 1	Hydro 1 was conducted using synthetic pore-water. The main aim of this phase was the characterization of hydraulic behavior of the undisturbed formation
01/02/00 10:20	11/04/00 10:20	Gas 1	Gas 1 was conducted using a step increase pressure pulse Nitrogen injection. The main aim of this phase was the calculation of the gas threshold pressure and gas mobility of the undisturbed formation
12/04/00 11:17	13/04/00 09:18	Frac	The Frac phase was conducted with the aim of initiating a hydro-frac in BGS2-Zone2, along the bedding plane perpendicular to the borehole. The goal was to propagate the frac to intersect Zone 2 of the other three boreholes.
13/04/00 10:48	14/04/00 08:46	Hydro 2	Hydro 2 was conducted using synthetic pore-water injection. The main aim of the phase was the characterization of the pressure-transmissivity relationship after the hydro-frac. The test was conducted as a step increase pressure pulse sequence, the last phase (HI) being conducted above the frac reopening pressure.
14/04/00 10:13	19/06/00 08:00	Gas 2	Gas 2 was conducted using pulse Nitrogen injection below the frac reopening pressure. The main aim of this phase was the characterization of the ability of the formation to transport gas after the hydro-frac.
21/06/00 15:04	21/11/00 12:21	Gas 3	Gas 3 was conducted as a constant rate Nitrogen injection followed by a long-term pressure recovery. The aim of this phase was to confirm the formation behavior observed during the Gas 2 phase and provide a high gas saturation along the fracture plain.
21/11/00 12:21	25/06/01 09:56	Hydro 3	Hydro 3 was conducted using synthetic pore-water injection. The main aim of the phase was the long term re-hydration of the fracture plane and the determination of the system transmissivity after fracture self-sealing. The phase was conducted as a two step long term constant pressure water injection (HI1 and HI2) followed by a pressure recovery phase (HIS2).
25/06/01 09:56	15/04/02 23:30	Gas 4	Gas 4 was conducted as a constant rate Nitrogen injection followed by a long-term pressure recovery. The aim of this phase was to derive the gas mobility and geometry of gas flow after a long term fracture self-sealing process.

The HG-C experiment followed on from the previous GS and GP-A experiments in the four boreholes BGS1-4. The experimental phase of HG-C started during Mont Terri Phase 12 in December 2006, with the installation of Solexperts FIMs in boreholes BGS3 and BGS4.

The major HG-C test events are listed in Table B.1. Phase 1 of HG-C involved constant head hydraulic testing into BGS2 interval 2 (TN 2007-13). Phase 2 included refurbishment of BGS-1 packer system and constant head gas injection in BGS2 interval 2 (TN 2008-80).

Table B.2: Test events during HG-C

Start	Borehole	Event	TN
14/12/2006 17:49	BGS2-i2	HI Step 1 12 bar	TN 2007-13
20/12/2006 12:16	BGS2-i2	HI Step 2 20 bar	TN 2007-13
10/01/2006 14:34	BGS2-i2	HI Step 3 30 bar	TN 2007-13
18/01/2007 13:28	BGS2-i2	HI Step 4 40 bar	TN 2007-13
12/02/2007 15:43	BGS2-i2	HI Step 5 50 bar	TN 2007-13
28/02/2007 16:16	BGS2-i2	HI Step 6 58 bar	TN 2007-13
08/03/2007 09:15	BGS2-i2	HI Step 5- 50 bar	TN 2007-13
21/03/2007 11:28	BGS2-i2	HI Step 4- 40 bar	TN 2007-13
21/03/2007 11:28	BGS2-i2	HI Step 3- 30 bar	TN 2007-13
04/04/2007 09:14	BGS2-i2	HI Step 2- 20 bar	TN 2007-13
16/04/2007 09:00	BGS2-i2	HI Step 1- 12 bar	TN 2007-13
27/04/2007 12:26	BGS2-i2	Shut-in	TN 2007-13
02/07/2007 13:45	BGS-1	Reinstall packer	TN 2008-80
05/02/2008 17:33	BGS2-i2	Gas HI-step1 (Back-P = 11.7 bar)	TN 2008-80
05/03/2008 14:34	BGS2-i2	Gas HI-step2 (Back-P =15.76 bar)	TN 2008-80
02/04/2008 12:29	BGS2-i2	Gas HI-step3 (Back-P =20.45 bar)	TN 2008-80
15/05/2008 12:40	BGS2-i2	Gas HI-step4 (Back-P =24.11 bar)	TN 2008-80
01/07/2008 11:20	BGS2-i2	Gas HI-step5 (Back-P = 30.05 bar)	TN 2008-80

During 2009 a new experiment phase (HG-D) was initiated with the drilling of HG-D1 borehole. Data from HG-D will be provided in a separate distribution. Modelling of HG-C will be used to develop calibrated models prior to prediction of the HG-D testing.

B.2 HG-C Coordinate system

The borehole locations are provided in Swiss UTM and a local coordinate system. The suggested local coordinate system has been chosen such that the origin is at the start of BGS1 and the Y-axis runs along the horizontal projection of the BGS-1 borehole (azimuth 329.3°). The boreholes and intervals in local coordinates are shown in Figure B.1.

Local coordinate system definition

Origin: (579382.769, 247611.011, 513.382)

Local X-Axis: (0.860, 0.511, 0.000)

Local Y-axis: (-0.511, 0.860, 0.000)

Local Z-axis: (0.0, 0.0, 1.0)

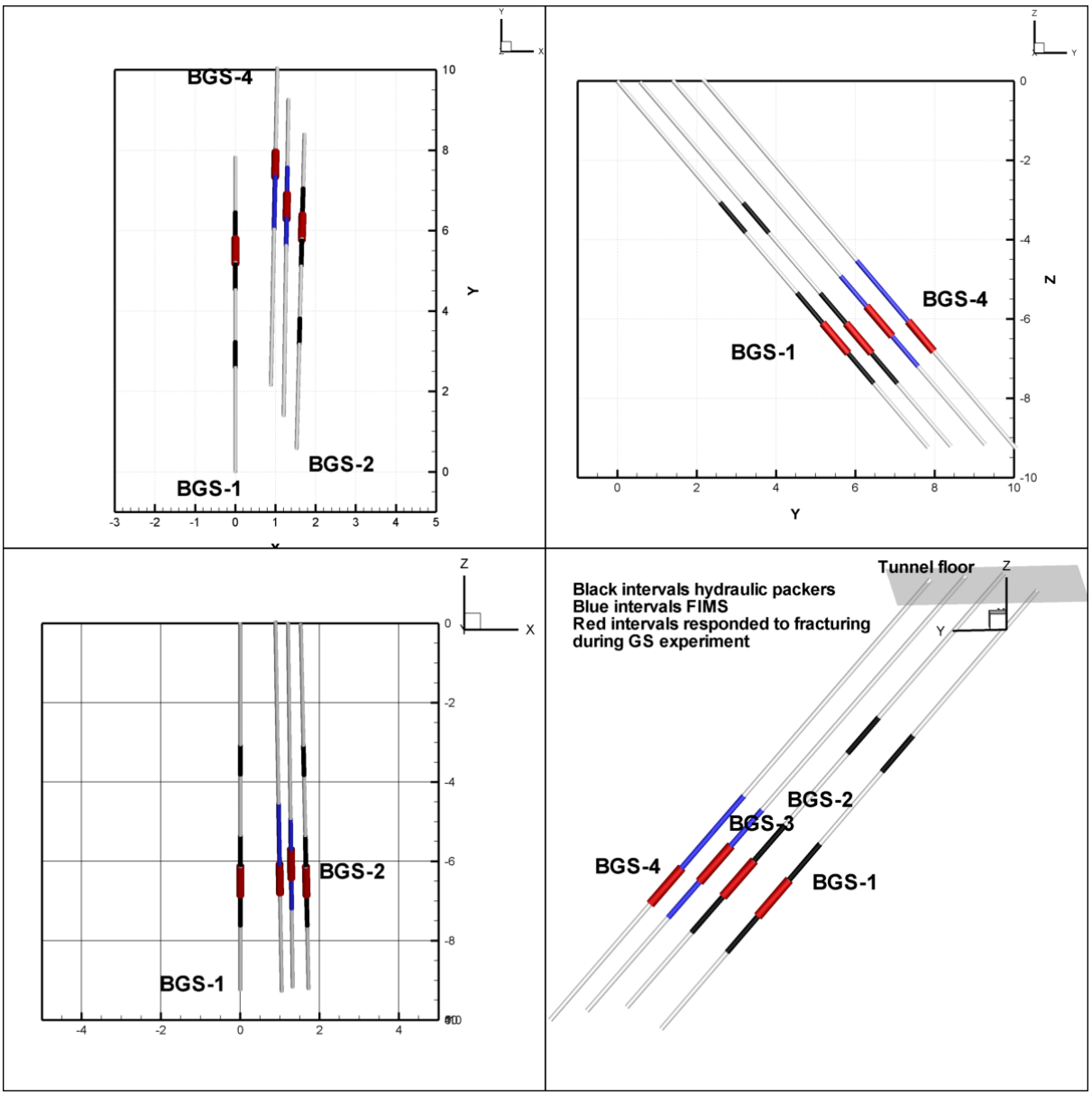

Figure B.1: HG-C borehole locations in local coordinate system.

B.3 Files provided in data distribution 4 (09/02/2010)

Table B.3: Files provided in HG-C data distribution

File	
HG-C Sensors FORGE V1.xslx	Borehole and instrument coordinates
GSGPA TestData.xls	Field test data from GS/GPS testing in 1999/2000
GSGPA Pressure monitoring.xls	
HG-CData141206-300609.xslx	Measured data
TN07-13 HGC Phase 12 Hydraulic tests and deformation measurements BGS2 Final	Phase 1 measurements and testing
TN2008-80 HGC Phase13 Hydraulic and gas test series in BGS-2	Phase 2 measurements and testing

B.4 References

Enachescu, C., Blümling, P., Castelao, A. and Steffen, P., 2002. Mont Terri GP-A and GS Experiments Synthesis Report. Nagra Internal Report NIB 02-51. Nagra, Wettingen, Switzerland.

Trick T. (2007). Mt. Terri HG-C Experiment Phase 1 First hydraulic tests and deformation measurements in borehole BGS-2 (Mt. Terri Phase 12) TN 2007-13.

Rösli, U., Trick T. (2008). Mt. Terri HG-C Experiment Phase 2: Hydraulic and gas test series in BGS-2 borehole and deformation measurements in BGS-3 and BGS-4 boreholes. Mt. Terri Phase 13 27.04.07 – 18.09.08.Mont Terri Technical Note TN 2008-80.