Characteristics of the Opalinus Clay at Mont Terri

Paul Bossart

**Reference: Bossart, P., & Thury, M. (2008). Mont Terri Rock Laboratory.
Project, programme 1996 to 2007 and results. Wabern: Reports
of the Swiss Geological Survey no. 3.**

General presentation of the parameters of the Opalinus Clay formation

The present compilation of the parameters of the Opalinus Clay at Mont Terri was prepared within the framework of the “Clay Club Catalogue” (Boisson, 2005[1]). This catalogue lists and compares the parameters of different clay formations at different sites.

The Opalinus Clay at Mont Terri (Dogger, Lower Aalenian, age about 180 My) is a shale formation that was formed as a marine sediment consisting of fine mud particles. It contains between 40-80% clay minerals and the present thickness is about 160 m. Three different facies can be distinguished: a shaly facies in the lower half of the sequence, a 15 metre thick sandy, carbonate-rich facies in the middle of the sequence and a sandy facies interstratified with the shaly facies in the upper part. One large tectonic fault zone was observed in the centre of the formation and could be traced on all tunnel intersections. This zone is called the “main fault” and is 1 to 3 metres thick. It contains a large number of single fault planes showing shear fibres with a shear movement sense that consistently indicates overthrusting.

Description of the Opalinus Clay formation at the Mont Terri rock laboratory

- An indication of the geological environment: the Opalinus Clay of Mont Terri is an overconsolidated shale. The maximum overburden was 1200 m and the present overburden is 280 m. The Opalinus Clay is overlain by a karstic aquifer of the Lower Dogger and underlain by a Liassic marl, also containing karstic phenomena. Hydraulically speaking, the Opalinus Clay can be considered to be an aquiclude sandwiched between two aquifers.

- Extent of the studied formation: the regional extent covers the whole of the Jura mountains (Switzerland and France), as well as the Swiss-German foreland basin (from Lake Geneva to Lake Constance). It also extends towards Baden-Württemberg in Southern Germany.

- Parameters relating to geology, mineralogy, rock chemistry, porewater chemistry, petrophysics and hydraulics are compiled from the Mont Terri project and its research programme and are presented in the Clay Club Catalogue, together with some geological illustrations:
  - Geological map: Figure AN 1-1
  - Geological profile: Figure AN 1-2

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[1] Boisson, J.-Y. (2005): Published report: detailed references can be found in Annex 6, publications

  - Stratigraphic sequence: Figure AN 1-3
  - Detailed lithological profile: Figure AN 1-4
  - Chloride concentration across the Opalinus Clay: Figure AN 1-5
  - Water content versus rock strength: Figure AN 1-6.

- An overview of the most important key parameters is given in Table AN 1-1. It is important to note that the Opalinus Clay contains a pronounced bedding anisotropy. This implies that parameter values parallel to the anisotropy plane are different to those normal to the anisotropy plane. Measurements therefore have to be carried out along different directions in Opalinus Clay samples or in differently directed boreholes.

Parameter	**Range**	**Best estimate**
Density, bulk saturated [g/cm^3]	2.40 - 2.53	**2.45**
Water content [saturated wt%]	5.0 - 8.9	**6.6**
Water loss porosity at 105°C [vol%]	12.6 - 21.1	**16.2**
Porosity, total physical [vol%]	14.0 - 24.7	**18.3**
Hydraulic conductivity [m/s]	2E-14 - 1E-12	**2E-13**
Thermal conductivity [W/mK]	1.0 - 3.1	**1.7**
Thermal conductivity parallel to bedding [W/mK]	-	**2.1**
Thermal conductivity normal to bedding [W/mK]	-	**1.2**
Heat capacity [J/Kg K]	-	**860**
Total dissolved solids in porewater [g/l]	5 - 20	**-**
Young's modulus normal to bedding [MPa]	2100 - 3500	**2800**
Young's modulus parallel to bedding [MPa]	6300 - 8100	**7200**
Poisson's ratio normal to bedding [-]	0.28 - 0.38	**0.33**
Poisson's ratio parallel to bedding [-]	0.16 - 0.32	**0.24**
Shear modulus [MPa]	800 - 1600	**1200**
Uniaxial compressive strength normal to bedding [MPa]	23.1 - 28.1	**25.6**
Uniaxial compressive strength parallel to bedding [MPa]	4.0 – 17.0	**10.5**
Uniaxial tensile strength normal to bedding [MPa]	-	**1**
Uniaxial tensile strength parallel to bedding [MPa]	-	**2**
Cohesion [MPa]	2.2 - 5	**3.6**
Internal friction angle [°]	**23 - 25**	**24**

Table AN 1-1: Range and best estimate values for key parameters of the Opalinus Clay at the Mont Terri rock laboratory.

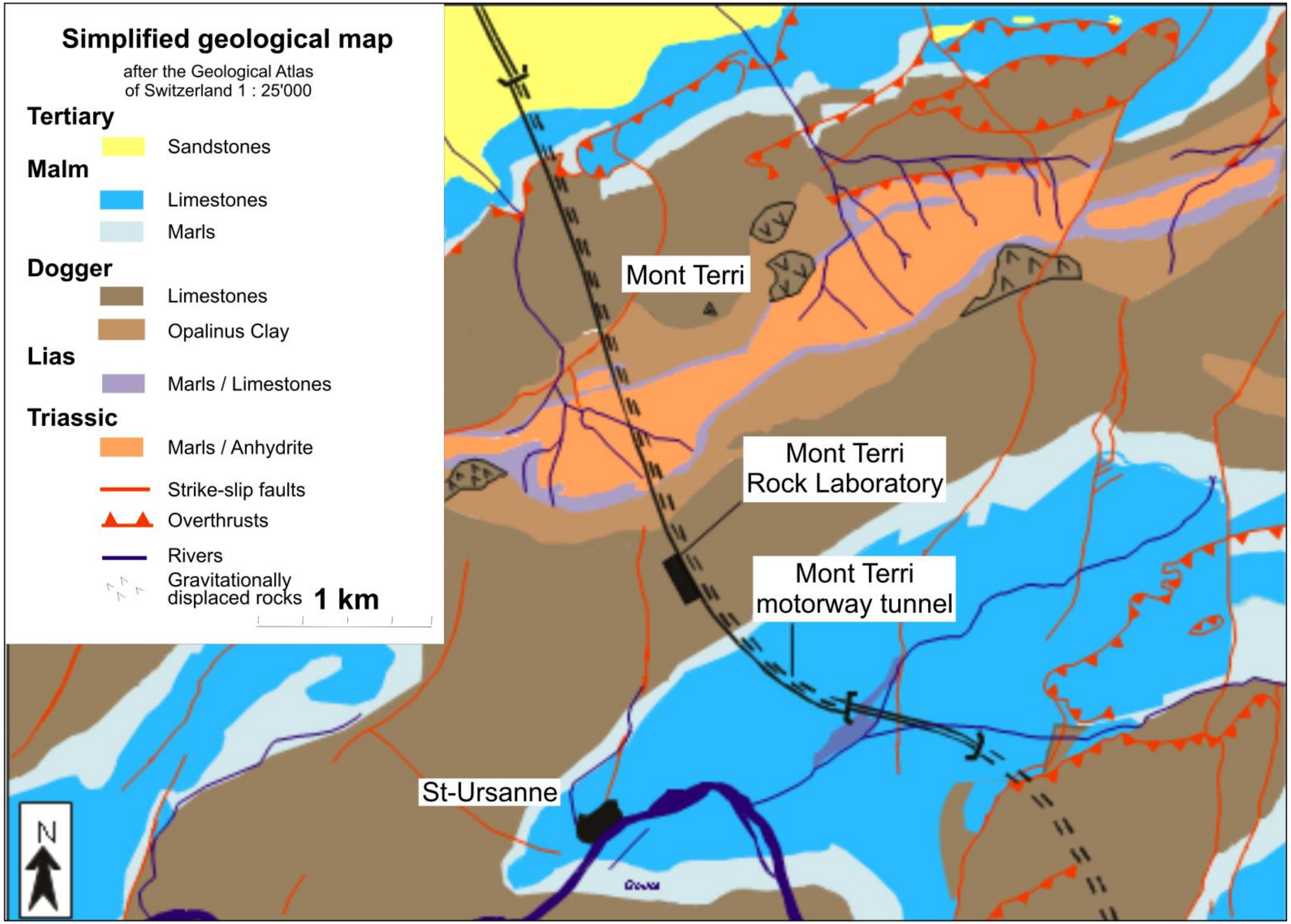

Figure AN 1-1: Simplified geological map of the Mont Terri anticline.

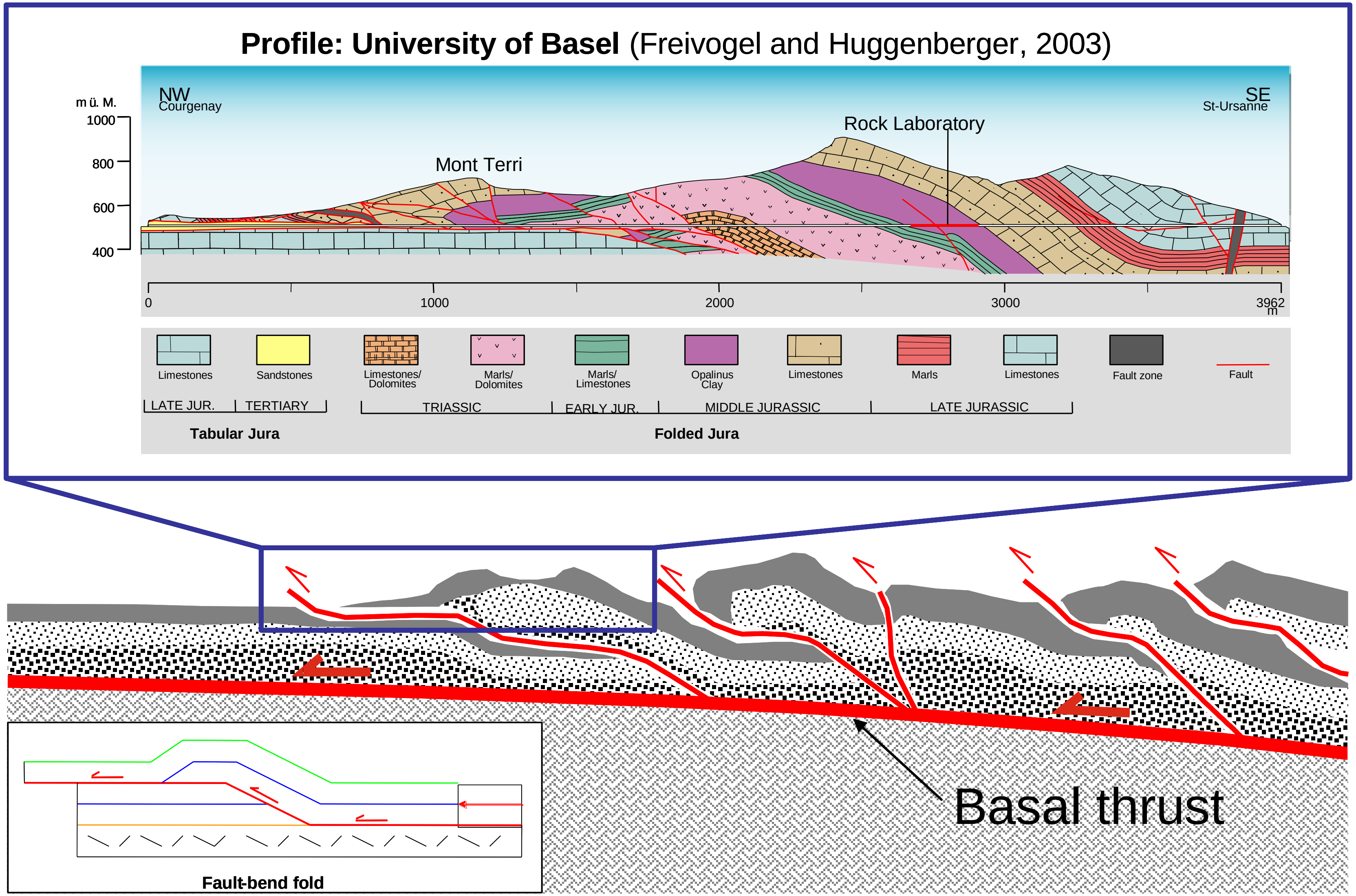

Figure AN 1-2: Geological profile along tunnel (above) and interpreted seismic profile (below).

Lithostratigraphic unit	Main lithology	Stage		Series
”Portlandian”	limestones	Tithonian		Upper Jurassic
Reuchenette Formation	limestones with thin intercalations of marls	Kimmeridgian		
Courgenay Formation	limestones	Upper	Oxfordian	
Vellerat Formation	marls and limestones			
St-Ursanne Formation	limestones	Middle		
Bärschwil Formation	shaly marls	Lower		
”Anceps-Athleta-Schichten”	marls	Callovian		Middle Jurassic
Dalle nacrée	limestones			
”Callovien-Ton”	marly clay			
Calcaire roux sableux	limestones	Bathonian		
Hauptrogenstein	(sandy) limestones	Bajocian		
”Lower Dogger”	(sandy) limestones			
Opalinus Clay	**shales (silty and sandy)**	**Aalenian**		
Jurensis Marls	marls and marly shales	Toarcian		Lower Jurassic
Posidonia Shales	bituminous shales			
Not defined in this study[1]	Not defined in this study[1]	Pliensbachian		
Gryphaea Limestones	limestones	Sinemurian		
Not defined in this study[1]	Not defined in this study[1]	Hettangian		
Keuper Marls	marls and anhydrite	Not defined in this study		Upper to Middle Triassic
Trigonodus Dolomite	dolomites and limestones			
Hauptmuschelkalk	limestones			
Anhydrite group	marls and anhydrite			

[1] It is still not known whether these lithostratigraphic units and lithologies were eroded or not deposited at all. They may also be represented by a condensed horizon.

Figure AN 1-3: Stratigraphic sequence of Triassic to Jurassic strata.

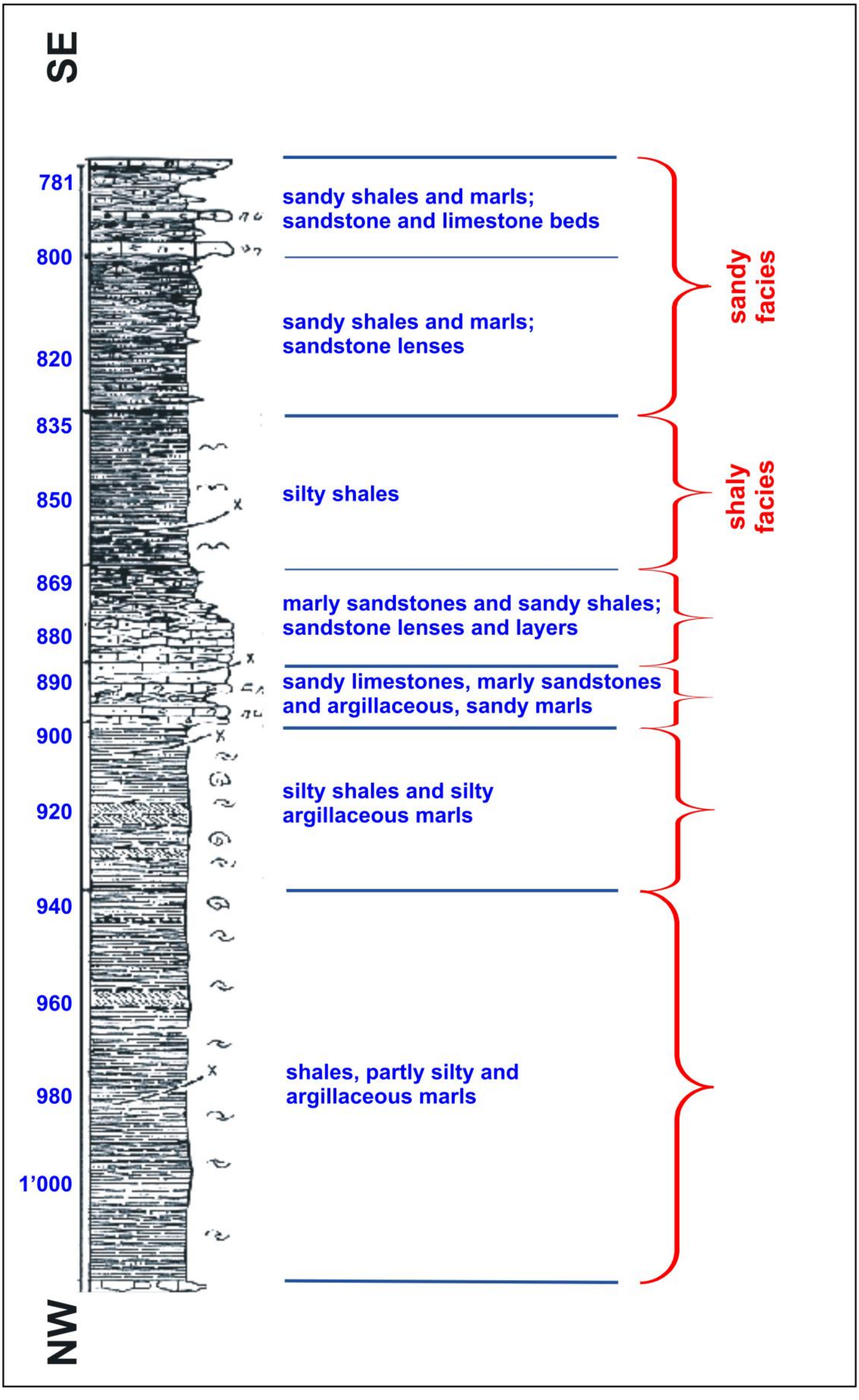

Figure AN 1-4: Detailed lithological profile along the Mont Terri rock laboratory

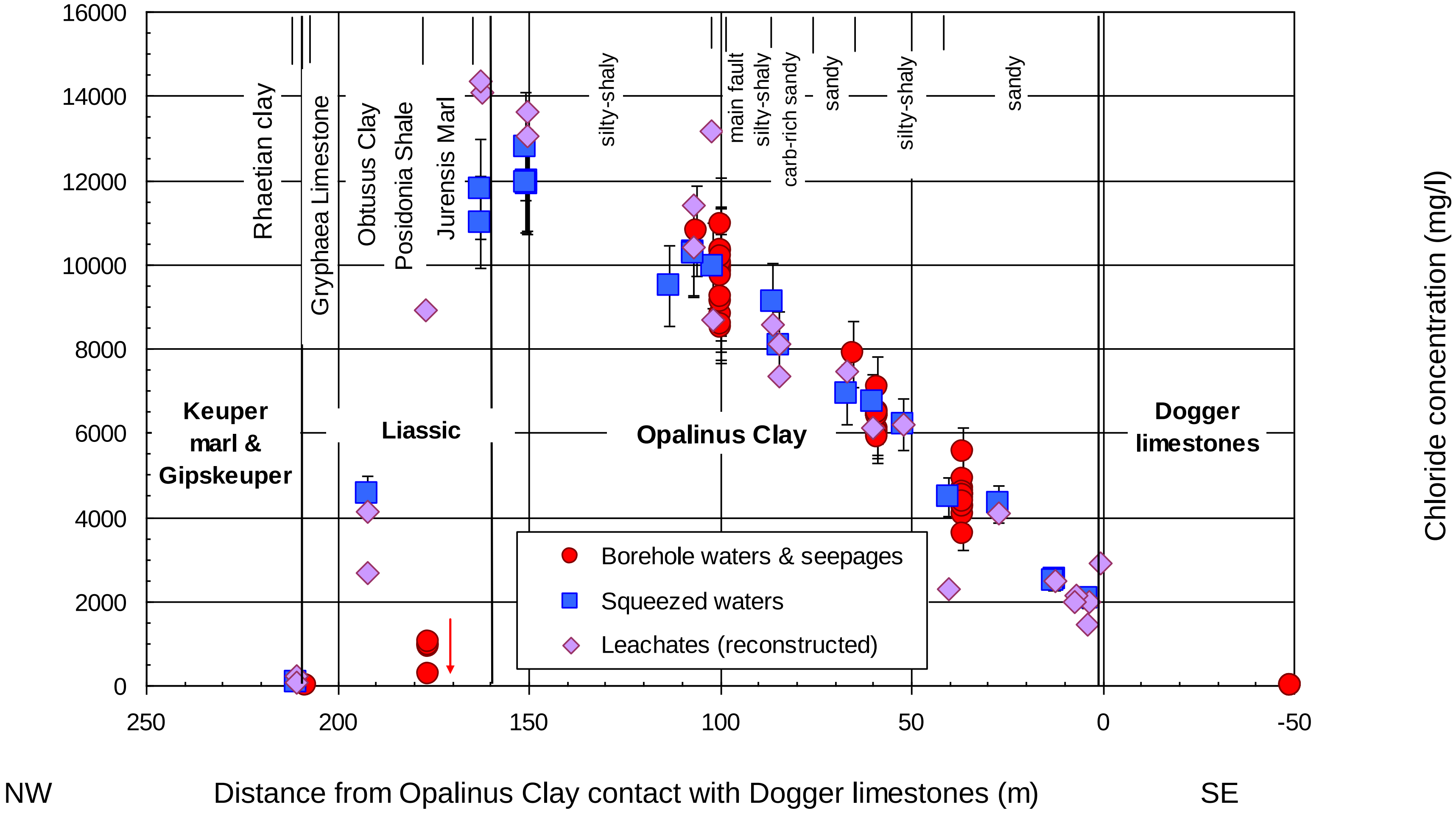

Figure AN 1-5: Chloride concentration profiles along the Mont Terri rock laboratory (Pearson et al., 2003)

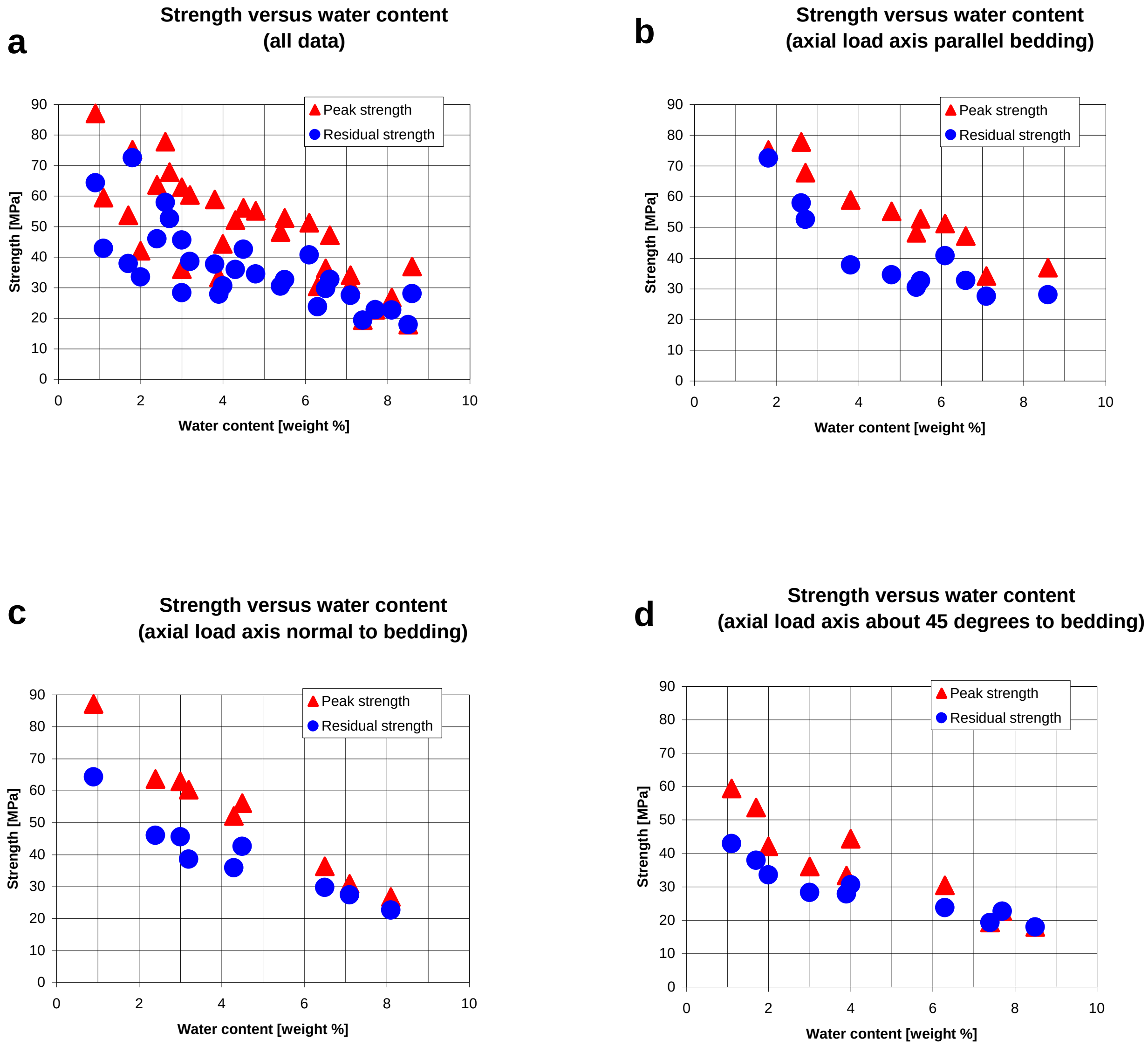

Figure AN 1-6: Strength dependence on water content: a) all samples; b) axial load, axis parallel to bedding; c) axial load, axis normal to bedding and d) axial load, axis 45 degrees to bedding, resulting in the smallest strength values.

GEOLOGICAL PARAMETERS	Description	Estimate	Scale 1)	Method	References
Stratigraphic unit [name]	Opalinston, Argiles à Opalinus, Opalinus Clay	-	°	°	1
Stratigraphic age [name]	Lower and middle part of Aalenian	-	°	°	1
Absolute age [Ma]	°	180	Site scale	Stratigraphic zoning by ammonites	2
Thickness [m]	**Apparent thickness** **True thickness**	160 90	Site scale	Mapping	3
Thickness remark	Apparent thickness of 160 m: unbalanced thickness, including internal tectonic thrusting. The true lithological thickness of the Opalinus Clay in the Mont Terri region is about 90 m.	-	°	°	4
Lithological description	The Opalinus Clay is an overconsolidated clay shale with three facies: shaly, sandy and carbonate-rich sandy.	-	°	°	5
Lithological description remarks	**Shaly facies:** argillaceous and marly shales with micas and nodular, bioturbated layers of marls. **Sandy facies:** marly shales with lenses of grey sandy limestones and mm-thick layers of white sandstones with pyrite. **Carbonate-rich sandy facies:** calcareous sandstones intercalated with bioturbated limestone beds with high detrital quartz content.				
Depositional environment	Marine; sedimentation took place in a degradational and oxic environment, with sulphate reduction during early diagenesis.	-	°	°	6
Present-day burial depth (top of formation) [m]	°	230	Site scale	Topographic mapping	5,7
Present-day burial depth (bottom of formation) [m]	°	320	Site scale	Topographic mapping	5,7
Present-day burial depth remarks	The Opalinus Clay formation dips with an average of 40 degrees towards SE. The topography above the rock laboratory is also inclined. 230 m (burial depth at top of formation) is the value at the southern entrance to the rock laboratory; 320 m is the value at the northern entrance.	-	°	°	5,7
Maximum burial depth [m]	°	1350	Site scale	Analysis of stratigraphic pile	7
Additional burial in the past (i.e. maximum minus present burial depth) [m]	°	1075	Site scale	Analysis of stratigraphic pile	7
Geological map and profile, sedimentary pile, detailed lithological profile along Mont Terri rock laboratory	°	-	°	°	**See Figures AN 4-1 to AN 4-4.**

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1E-03-1E-01m, micro scale <1E-03 m.

MINERALOGY [% total dry weight]	**Minimum value**	**Best estimate**	**Maximum value**	**Scale 1)**	**Method**	**Reference**
Sum of all clay minerals	28.0	66.0	93.0	Drillcore & sample	XRD	8
Sum of all clay minerals < 2 µm	27.0	53.0	78.0	Drillcore & sample	XRD	13
Remark on sum of all clay minerals: total clay mineral content: these data have been derived from Table 4 of MAZUREK (1998). As this table indicates, the analyses refer only to 4 samples and are thus not reliable. The total clay mineral content of the mineral fraction <2 micrometres is based on 20 samples and is thus more reliable (BLAESI et al., 1991).						
Illite	15.0	23.0	30.0	Drillcore&sample	XRD	9,10,11,35
Chlorite	3.0	10.0	18.0	Drillcore&sample	XRD	9,10,11,35
Kaolinite	15.0	22.0	37.0	Drillcore&sample	XRD	9,10,11,35
Illite/smectite ML	5.0	11.0	20.0	Drillcore&sample	XRD	9,10,11,35
Quartz	10.0	13.7	32.0	Drillcore&sample	XRD	9,10,11,35
Feldspars-K	0.0	1.0	6.0	Drillcore&sample	XRD	9,10,11,35
Feldspars-albite	0.0	1.0	2.0	Drillcore&sample	XRD	9,10,11,35
Calcite	4.0	13.0	22.0	Drillcore&sample	XRD	9,10,11,35
Dolomite/ankerite	0.0	0.5	1.0	Drillcore&sample	XRD	9,10,11,35
Siderite	0.0	3.0	6.0	Drillcore&sample	XRD	9,10,11,35
Pyrite	0.0	1.1	3.0	Drillcore&sample	XRD	9,10,11,35
Gypsum	0.0	0.20	0.5	°	°	9,10,11
Remark on gypsum: gypsum minerals are mainly bound to the excavation damaged zone (EDZ). Small gypsum spots (<0.2 mm) are frequently observed on unloading fracture surfaces in the EDZ (in the first 70 cm of the tunnel wall), indicating oxidation of pyrite in an interconnected EDZ fracture network (air can pass from the tunnel through this fracture network; oxygen is thus available for oxidation).						
1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1E-03-1E-01m, micro scale <1E-03 m.						
Celestite	0.00	0.25	1.00	°	°	expert judgement
Baryte	0.00	0.25	1.00	°	°	expert judgement
Accessory minerals	-	-	-	°	°	not analysed
Vitrinite reflectivity	0.40	0.58	1.50	Drillcore&sample	°	11,12,35
Remark on vitrinite reflectivity: the maturity of the organic matter is relatively low, as indicated by the vitrinite reflectivity. The Opalinus Clay did not reach the main stage of petroleum formation. One reason is the bacterial sulphate reduction during diagenesis. Thus, no petroleum potential can be attributed to the Opalinus Clay.						
Organic Carbon	0.40	0.80	1.20	Drillcore&sample	Organic geochemical techniques (screening pyrolysis, transmitted light microscopy; vitrinite reflectance)	11,12,35
Remark on organic carbon: three sources of organic matter were identified: 1) marine algae, 2) terrestrial plant detritus and 3) re-sedimented matter. Bitumen can be related to 1) and 2) and kerogens to 3). Total organic matter is mostly kerogen-III type. Due to sulphate reduction during diagenesis, the overall preservation potential of organic matter in the Opalinus Clay was very low. Humic substances are only about 0.15%, which is in agreement with the relatively low TOC values.						11,12

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm

ROCK CHEMISTRY	**Minimum value**	**Best estimate**	**Maximum value**	**Scale 1)**	**Method**	**Reference**
Total CEC [meq/100 g of rock]	9.44	11.10	13.35	Drillcore&sample	Ni-en solution	12,13
Exchangeable Na [meq/100 g of rock]	3.61	5.10	6.37	Drillcore&sample	Ni-en solution	12
Exchangeable K [meq/100 g of rock]	0.58	0.80	0.92	Drillcore&sample	Ni-en solution	12
Exchangeable Ca [meq/100 g of rock]	2.25	3.00	3.58	Drillcore&sample	Ni-en solution	12
Exchangeable Mg [meq/100 g of rock]	1.55	2.00	2.38	Drillcore&sample	Ni-en solution	12
Exchangeable Sr [meq/100 g of rock]	0.10	0.20	0.36	°	°	°
Remark on CEC: only the CEC values related to the Ni-en solution are presented, resulting in a mean value of 11.1 meq/100 g. Mean total CEC values derived with other solutions are higher: 12.3 meq/100 g with Na-acetate and 16.0 meq/100 g with Co-hexamine. Note that the total CEC is normally higher than the sum of the exchangeable cations due to the fact that the CEC of H^+ and NH_4 are not included in the sum, but in the total.						
Sum of exchangeable cations [meq/g]	8.09	11.10	13.61	Drillcore&sample	Sum of individual cations	12

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

POREWATER CHEMISTRY (page 1 of 3)	**Description**	**Best estimate**	**Scale 1)**	**Method**	**Reference**
Water type	°	$Na-Cl-SO_4$	°	°	°
Water type remark	Sodium-chloride-sulphate water				
Mineralisation TDS [mg/l]	Total Dissolved Solids	18296	Borehole test interval	Sum of cation and anion concentrations	°
Ionic strength [mol/kgH_2O]	°	0.350	Borehole test interval	Calculated from stoichiometric values	12
pH [-log H+]	pH field	7.96	Borehole test interval	pH-meter in flow-through cell	11,12
pH [-log H+]	pH lab	7.30	Borehole test interval	pH-meter	11,12
pCO_2, total dissolved [log bars]	water sample	-3.58	Modelling	Calculated from measured pH and TIC / alkalinity	11,12
pCO_2, total dissolved [log bars]	drillcore	-2.69	Drillcore measurements	Measurement of CO_2 degassing of a core placed in a sealed cell	14
Eh [mV]	Eh field	-227	Borehole test interval	Platinum electrode in Ar atmosphere	36
Remark on measured pH and Eh values: geochemical modelling confirms that these measured pH and Eh values from water samples taken from the BWS-A1 test interval represent the important characteristics of the in situ porewater.					
Remark on Eh: true Eh values of porewater can generally not be evaluated in situ and are thus normally estimated by geochemical modelling. However, this Eh value of -227 mVolt was measured in the PC (porewater chemistry) experiment in the Mont Terri rock laboratory in November 2003, where the Eh evolution was measured downhole over a period of at least 1.5 years, starting in April 2002. The experiment is still ongoing (September 04) and the Eh measurements are still decreasing.					
Electrical cond. [µS/cm]	°	26920	Borehole test interval	Electrical conductivity sensor in flow-through cell	11,12
Sample temperature [C°]	°	13.0	Borehole test interval	Temperature sensor in flow-through cell	11,12
Alkalinity [mol/l]	analysed from sample	2.50E-03	Borehole test interval	Potentiometric titration	11,12
Alkalinity [mol/l]	calculated from measured pH and TIC	7.49E-04	Modelling	°	11,12
TOC [mg/l]	Total Organic Carbon	14	Borehole test interval	°	11,12
TIC [mg/l]	Total Inorganic Carbon	8.50	Borehole test interval	°	11,12

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

POREWATER CHEMISTRY (page 2 of 3)	**Best estimate**	**Scale 1)**	**Method**	**Reference**
Concentration of water components				
Remark on location of test interval to which analyses of **cations**, **anions** and **other parameters** belong: this water corresponds to the reference analyses of samples from borehole BWS-A1 (shaly facies). The test interval of this borehole is partly in the undisturbed matrix and partly in the main fault. It has to be clearly noted that there is a whole range of concentrations across the Opalinus Clay, due to out-diffusion into the over- and underlying aquifers. This can be best seen in the chloride profiles (see Figure 5 of the geological illustrations).				
Cations [mg/l]				
Ca	609.0	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Li	0.4	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Na	5640	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
K	43.4	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Mg	415.0	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Fe (Fe^{2+})	0.14	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Remark on Fe concentration: only one value for iron (Fe^{2+}) from borehole BWS-A3 is available. Iron contamination due to downhole instrumentation may explain this high value.				
Al	0.013	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Si	1.61	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
NH_4	10.2	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Ba	0.019	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
B	1.61	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Mn (Mn^{2+})	0.346	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12
Sr	35.00	Borehole test interval	Inductively-coupled atomic emission spectrometry (ICP-AES) and ion chromatography.	11,12

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

POREWATER CHEMISTRY (page 3 of 3)	**Description**	**Best estimate**	**Scale 1)**	**Method**	**Reference**
Concentration of water components					
Remark on location of test interval to which analyses of **cations**, **anions** and **other parameters** belong: this water corresponds to the reference analyses of samples from borehole BWS-A1 (shaly facies). The test interval of this borehole is partly in the undisturbed matrix and partly in the main fault. It has to be clearly noted that there is a whole range of concentrations across the Opalinus Clay, due to out-diffusion into the over- and underlying aquifers. This can be best seen in the chloride profiles (see Figure AN 4-5).					
Anions [mg/l]					
Cl	**See Figure AN 4-5**	10,170	Borehole test interval	Ion chromatography and $AgNO_3$ titration.	11,12
SO4	°	1,320	Borehole test interval	Ion chromatography	11,12
Br	°	35.0	Borehole test interval	Ion chromatography	11,12
I	°	2.2	Borehole test interval	Ion chromatography	11,12
NO3	°	10.0	Borehole test interval	Ion chromatography	11,12
NO2	°	2.0	Borehole test interval	Ion chromatography	11,12
F	°	0.75	Borehole test interval	Ion chromatography	11,12
Other parameters					
$^{34}S/^{32}S$	°	-	Borehole test interval	°	11,12
$^{37}Cl/^{35}Cl$	°	-	Borehole test interval	°	11,12
delta ^{18}O [%o SMOW]	°	-8.53	Borehole test interval	Direct diffusive exchange of porewater	12
delta ^{2}H [%o SMOW]	°	-54.70	Borehole test interval	Direct diffusive exchange of porewater	12
Tritium [TU]	°	0	Borehole test interval	Beta decays with scintillometer	12
Remark on detected tritium: generally, no tritium was measured in the Opalinus Clay. Exception: during the excavation of the new gallery, a sudden increase in discharge from the main fault was observed (test interval of borehole BWS-A1). In the same sample, a tritium concentration of 7.3 TU was measured.					

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

PETROPHYSICAL PARAMETERS (page 1 of 2)	**Minimum value**	**Best estimate**	**Maximum value**	**Scale 1)**	**Method**	**Reference**
Bulk density (saturated) [t/m^3]	2.40	2.45	2.53	Drillcore&sample	ISRM, 1981	15, 16
Bulk density dry [t/m^3]	2.28	2.31	2.32	Drillcore&sample	ISRM, 1981	15, 35
Average grain density [t/m^3]	2.70	2.74	2.77	Drillcore&sample	ISRM, 1981	15, 35
Water content (weight loss at 105°C) [% dry weight]	5.3	7.0	9.8	Drillcore&sample	ISRM, 1981	12, 15
Water content (weight loss at 105°C) [% saturated weight]	5.0	6.6	8.9	Drillcore&sample	ISRM, 1981	12, 15
Remark on water content: the gravimetric water content, WC, can be described on a mass basis relative to either the dry mass (Mgr) or total mass (Mtot) of the rock. The dry water content WC_dry is the mass of water divided by Mgr; the saturated water content WC_wet is the mass of water divided by Mtot.						
Total physical porosity	14.0	18.3	24.7	Drillcore&sample	ISRM, 1981	12, 15, 37
Water loss porosity (calculated from weight loss at 105°C and grain density) [vol-%]	12.6	16.2	21.1	Drillcore&sample	ISRM, 1981	12, 15, 37
Remark on total physical porosity and water content porosity: the total physical porosity n_tot can be derived from the dry bulk density (rho_bulk_dry) and the grain density (rho_grain) of the rock: n_tot [%] = 100x(1 - (rho_bulk_dry/rho_grain)). The water content porosity n_wc is calculated from the water content of a saturated sample (WC_wet, measured) and its sample grain density (rho_grain, measured). If only water diffusion in the clay is investigated, the water content porosity should be used. The formula for the water content porosity is as follows: n_wc [%] = (WC_wet x rho_grain)/((0.01 x WC_wet x rho_grain) + (1-0.01 x WC_wet) x rho_water). Note that water content porosity contains a larger error due to the fact that not all porewater is extractable at 105 degrees Celsius. The same is true for the total physical porosity, since the dry bulk density is not fully dry.						
Hg injection porosity total [vol-%]	9.75	10.60	11.42	Drillcore&sample	Mercury injection	17
Remark on Hg injection porosity: these values can be considered as the connected porosity in the Opalinus Clay.						
Macro-porosity [vol-%]	0.61	0.97	1.32	Drillcore&sample	Mercury injection	17
Micro-porosity [vol-%]	8.93	9.65	10.36	Drillcore&sample	Mercury injection	17
Geochemical porosity [vol-%]	8.0	9.0	10.0	Drillcore&sample	Leaching experim.	12, 18
Remark on geochemical porosity: the best estimate of 9% corresponds to the geochemical porosity of chloride. Other ions have different geochemical porosities. In general, geochemical porosities are mainly used for the modelling of solute transport (e.g. diffusion of solutes in unfractured Opalinus Clay). Geochemical porosities can be calculated from leaching experiments together with measured solute concentrations from porewater samples and the measured (saturated) bulk density. Generally, geochemical porosities are smaller than water content porosities, since solutes do not have access to the entire water content of the clay.						
Specific surface internal [m^2/g]	112	130	147	Drillcore&sample	Adsorption	19, 20, 21
Specific surface external [m^2/g]	24	31	37	Drillcore&sample	BET	19, 20, 21
Thermal parameters derived from laboratory tests						
Thermal conductivity [W/mK]	1.0	2.0	3.1	Drillcore&sample	Therm. cond. measurement	22, 23
Heat capacity [J/kgK]	970	1155	1340	Drillcore&sample	Therm. cond. measurement	22, 23
Remark on thermal parameters derived from laboratory testing: the bedding anisotropy of Opalinus Clay has a large effect on the values for thermal conductivity. Generally, the minimum value is the thermal conductivity perpendicular to the bedding plane and the maximum value is that parallel to the bedding.						

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

PETROPHYSICAL PARAMETERS (page 2 of 2)	Minimum value	Best estimate	Maximum value	Scale 1)	Method	Reference
Thermal parameters derived from in situ testing						
Thermal conductivity parallel to bedding [W/mK]	-	2.1	-	In situ heater test	THM modelling	45
Thermal conductivity normal to bedding [W/mK]	-	1.2	-	In situ heater test	THM modelling	45
Thermal conductivity, mean [W/mK]	-	1.7	-	In situ heater test	THM modelling	45
Heat capacity [J/kgK]	-	860	-	In situ heater test	THM modelling	45
Thermal expansion [1/C]	1.5E-06	4.2E-06	1.0E-05	In situ heater test	THM modelling	45
Remark on thermal in situ parameters: these parameters originate from the HE-D experiment (THM behaviour of the host rock). Remark on thermal expansion: effect of bedding anisotropy has to be considered. Higher (max) value parallel to bedding, lower (min) value normal to bedding						
Seismic velocities						
Vp normal to bedding [m/s]	2220	2620	3020	Drillcore&sample	Ultrasonic velocity, method described in ISRM (1981), p. 105-110.	15, 16
Vp parallel to bedding [m/s]	2450	3030	3610	Drillcore&sample	Ultrasonic velocity, method described in ISRM (1981), p. 105-110.	15, 16
Vs normal to bedding [m/s]	1260	1510	1760	Drillcore&sample	Ultrasonic velocity, method described in ISRM (1981), p. 105-110.	15, 16
Vs parallel to bedding [m/s]	1840	1960	2080	Drillcore&sample	Ultrasonic velocity, method described in ISRM (1981), p. 105-110.	15, 16
Seismic velocity anisotropy Vp/Vs parallel to bedding	1.33	1.55	1.74	Drillcore&sample	Ultrasonic velocity, method described in ISRM (1981), p. 105-110.	15, 16
Seismic velocity anisotropy Vp/Vs normal to bedding	1.72	1.74	1.76	Drillcore&sample	Ultrasonic velocity, method described in ISRM (1981), p. 105-110.	15, 16

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

HYDRAULIC PARAMETERS (page 1 of 2)	**Minimum value**	**Best estimate**	**Maximum value**	**Scale 1)**	**Method**	**Reference**
Flow and solute transport parameters						
Hydraulic conductivity [m/s]	2E-14	2E-13	1E-12	In situ test	Hydrogeol. testing	11, 26
Hydraulic conductivity parallel to bedding [m/s]	-	2E-13	-	In situ test	Hydrogeol. testing	
Hydraulic conductivity normal to bedding [m/s]	-	4E-14	-	Best estimate	-	
Specific storativity [m^{-1}]	1.E-07	2.E-06	1.E-04	In situ test	Hydrogeol. testing	11, 26
Remark on hydraulic anisotropy: no systematic testing (field or laboratory) or modelling has been carried out so far for the derivation of the hydraulic anisotropy (e.g. testing and evaluation of parameters in differently oriented boreholes relative to the bedding). Quantitatively, it can be stated that the hydraulic conductivity parallel to bedding is higher than that normal to bedding. Furthermore, it is assumed that the isotropic hydraulic conductivity value lies close to the value parallel to bedding. A hydraulic conductivity aspect ratio (conductivity parallel to bedding divided by conductivity normal to bedding) of 5 is suggested as a best guess.						
Osmotic effiency [%]	4	6	8	In situ test	Fluid exchange	24, 25
Osmotic permeability [m^{5}s^{-1}mole^{-1}]	-3.45E-15	-7.48E-15	-1.15E-14	In situ test	Fluid exchange	24, 25
Remark on osmotic efficiency: exchange of test interval fluid with deionised water resulted in a higher osmotic efficiency (8%) than that with a 100 g/l NaCl solution (4%). The ratio of osmotic efficiency of non-concentrated and highly concentrated fluid is thus 2. Generally, osmotic permeabilities and thus osmotic efficiencies are greater at low solute concentrations than at high values.						
Diffusion parameters derived from laboratory tests						
Effective diffusion coefficient D_e of tritium parallel to bedding [m^2/s]	4.0E-11	5.4E-11	1.0E-10	Drillcore&sample	Through diffusion	27, 28, 43
Effective diffusion coefficient D_e of tritium normal to bedding [m^2/s]	1.0E-11	1.5E-11	2.0E-11	Drillcore&sample	Through diffusion	27, 28
Diffusion anisotropy of tritium (ratio parallel/normal)	3.00	3.60	5.00	Drillcore&sample	Through diffusion	27, 28
Effective porosity n_e of tritium	0.15	0.16	0.17	Drillcore&sample	Through diffusion	42
Effective diffusion coefficient D_e of iodine parallel to bedding [m^2/s]	8.0E-12	1.1E-11	1.4E-11	Drillcore&sample	Through diffusion	27, 28
Effective diffusion coefficient D_e of iodine normal to bedding [m^2/s]	2.4E-12	3.4E-12	4.2E-12	Drillcore&sample	Through diffusion	27, 28
Diffusion anisotropy of iodine (ratio parallel/normal)	3.33	3.25	3.33	Drillcore&sample	Through diffusion	27, 28
Effective diffusion coefficient D_e of chloride parallel to bedding [m^2/s]	1.8E-11	4.3E-11	6.8E-11	Drillcore&sample	Through diffusion	27, 28
Effective diffusion coefficient D_e of chloride normal to bedding [m^2/s]	-	4.8E-12	-	Drillcore&sample	Through diffusion	27, 28
Diffusion anisotropy of chloride (ratio parallel/normal)	-	22.50	-	Drillcore&sample	Through diffusion	27, 28
Effective porosity n_e of chloride	0.06	0.09	0.12	Drillcore&sample	Through diffusion	27, 28
Effective diffusion coefficient D_e of bromide parallel to bedding [m^2/s]	1.7E-11	3.1E-11	4.5E-11	Drillcore&sample	Through diffusion	43
Effective porosity n_e of bromide	0.10	0.13	0.15	Drillcore&sample	Through diffusion	43
Effective diffusion coefficient D_e of caesium parallel to bedding [m^2/s]	-	2.6E-10	-	Drillcore&sample	Through diffusion	43
Effective porosity n_e of caesium	-	0.17	-	Drillcore&sample	Through diffusion	43
Effective diffusion coefficient D_e of ^{22}Na parallel to bedding [m^2/s]	-	7.2E-11	-	Drillcore&sample	Through diffusion	43
Effective porosity n_e of ^{22}Na	-	0.17	-	Drillcore&sample	Through diffusion	43
Retention parameter K_d of ^{22}Na	-	0.18	-	Drillcore&sample	Through diffusion	43
Effective diffusion coefficient D_e of ^{85}Sr parallel to bedding [m^2/s]	-	6.5E-11	-	Drillcore&sample	Through diffusion	43
Effective porosity n_e of ^{85}Sr	-	0.17	-	Drillcore&sample	Through diffusion	43
Retention parameter K_d of ^{85}Sr	-	1.40	-	Drillcore&sample	Through diffusion	43
Remark on diffusion coefficients measured in the laboratory: diffusion coefficients were measured in the laboratory by CEA (France), DAMRI (France), Environmental Canada (Canada), Ciemat (Spain), PSI (Switzerland) and Harwell (England).						

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

HYDRAULIC PARAMETERS (page 2 of 2)	**Minimum value**	**Best estimate**	**Maximum value**	**Scale 1)**	**Method**	**Reference**
Diffusion parameters derived from in situ testing						
Effective diffusion coefficient D_e of tritium parallel to bedding [m^2/s]	5.0E-11	5.9E-11	6.8E-11	Borehole&overcore	Borehole diffusion	27, 28, 38, 39, 40, 41, 42, 44
Effective porosity n_e of tritium	0.12	0.16	0.19	Borehole&overcore	Borehole diffusion	27, 28, 38, 39, 40, 41, 42, 44
Effective diffusion coefficient D_e of iodine parallel to bedding [m^2/s]	1.3E-11	2.2E-11	3.0E-11	Borehole&overcore	Borehole diffusion	27, 28, 38, 39, 40, 41, 42, 44
Effective porosity n_e of iodine	0.05	0.10	0.15	Borehole&overcore	Borehole diffusion	27, 28, 38, 39, 40, 41, 42, 44
Effective diffusion coefficient D_e of bromide parallel to bedding [m^2/s]	-	3.0E-11	-	Borehole&overcore	Borehole diffusion	40, 41, 42
Effective porosity n_e of bromide	-	0.10	-	Borehole&overcore	Borehole diffusion	40, 41, 42
Effective diffusion coefficient D_e of ^{22}Na parallel to bedding [m^2/s]	-	7.2E-11	-	Borehole&overcore	Borehole diffusion	42
Effective porosity n_e of ^{22}Na	-	0.18	-	Borehole&overcore	Borehole diffusion	42
Retention parameter K_d of ^{22}Na	-	0.2	-	Borehole&overcore	Borehole diffusion	42
Effective diffusion coefficient D_e of ^{85}Sr parallel to bedding [m^2/s]	-	7.0E-11	-	Borehole&overcore	Borehole diffusion	40, 41
Effective porosity n_e of ^{85}Sr	-	0.15	-	Borehole&overcore	Borehole diffusion	40, 41
Retention parameter K_d of ^{85}Sr	-	1.0	-	Borehole&overcore	Borehole diffusion	40, 41
Effective diffusion coefficient D_e of caesium parallel to bedding [m^2/s]	2.3E-10	2.7E-10	3.0E-10	Borehole&overcore	Borehole diffusion	40, 41, 42
Effective porosity n_e of caesium	0.17	0.18	0.18	Borehole&overcore	Borehole diffusion	40, 41, 42
Effective diffusion coefficient D_e of ^{60}Co parallel to bedding [m^2/s]	-	6.0E-11	-	Borehole&overcore	Borehole diffusion	40, 41, 42
Effective porosity n_e of ^{60}Co	-	0.15	-	Borehole&overcore	Borehole diffusion	40, 41
Retention parameter K_d of ^{60}Co	-	90.0	-	Borehole&overcore	Borehole diffusion	40, 41
Effective diffusion coefficient D_e of ^{6}Li parallel to bedding [m^2/s]	-	7.0E-11	-	Borehole&overcore	Borehole diffusion	44
Effective porosity n_e of ^{6}Li	-	0.16	-	Borehole&overcore	Borehole diffusion	44
Retention parameter K_d of ^{6}Li	-	8.8	-	Borehole&overcore	Borehole diffusion	44
Remark on diffusion coefficients measured in situ: diffusion experiments were also carried out in situ in boreholes at the Mont Terri rock laboratory. All these experiments rely on the same principle: diffusion of tracers into a borehole wall and subsequent overcoring of the test interval. The measured evolution of the test interval concentration together with the tracer profiles of the overcore then serve to evaluate effective diffusion coefficients and diffusion porosities. These are mainly the DI experiment (HTO and iodine in the matrix), the FM-C experiment (helium, HTO and iodine in a tectonic fault zone, the main fault) and the DI-A experiment (HTO, iodine, bromide, ^{22}Na, ^{85}Sr, caesium, ^{60}Co)) and the DI-B experiment (HTO, iodine and ^{6}Li). All concentrations of radioactive tracers were below the exemption limit.						
In situ rock profile measurements along the Mont Terri rock laboratory of ^{2}H, ^{18}O, Na, Cl and Br were also analysed and the corresponding diffusion parameters evaluated. Only effective diffusion values normal to bedding were derived and for ^{2}H and ^{18}O are 1.4E-11 m2/s, for Na 0.5E-11 m2/s and for Cl and Br 0.25E-11m2/s. For details see references 30-33.						

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

ROCK MECHANICAL PARAMETERS (page 1 of 3)	**Minimum value**	**Best estimate**	**Maximum value**	**Scale 1)**	**Method**	**Refe-rence**
Uniaxial compressive strength normal to bedding [MPa]	23.1	25.6	28.1	Drillcore & sample	No confining pressure, short-term laboratory tests. Method described in ISRM (1981), p. 113-116.	15, 16 **(Figure AN 4-6)**
Uniaxial compressive strength parallel to bedding [MPa]	4.0	10.5	17.0	Drillcore & sample	No confining pressure, short-term laboratory tests. Method described in ISRM (1981), p. 113-116.	15, 16
Remark on uniaxial compressive strength: for excavation progress with a road header in the Mont Terri rock laboratory, the higher value of 25 MPa should be used. For the planning of the lining and the stability performance, a lower value of 10 MPa should be used.						
Uniaxial compressive strength anisotropy	1.65	2.44	5.78	Drillcore & sample		
Uniaxial tensile strength normal to bedding [MPa]	-	1	-	Drillcore & sample	No confining pressure. Method described in ISRM (1981), p. 117-121.	15, 16
Uniaxial tensile strength parallel to bedding [MPa]	-	2	-	Drillcore & sample	No confining pressure. Method described in ISRM (1981), p. 117-121.	15, 16
Uniaxial tensile strength anisotropy	-	0.5	-	Drillcore & sample		
Dynamic Poisson's Ratio normal to bedding [-]	0.26	0.28	0.30	Drillcore & sample	Derived from ultrasonic velocity measurements on drillcores. Method described in ISRM (1981), p. 105-110.	15, 16
Dynamic Poisson's Ratio parallel to bedding [-]	0.21	0.24	0.27	Drillcore & sample	Derived from ultrasonic velocity measurements on drillcores. Method described in ISRM (1981), p. 105-110.	15, 16
Dynamic Young's Modulus normal to bedding [MPa]	10300	11900	13500	Drillcore & sample	Derived from ultrasonic velocity measurements on drillcores. Method described in ISRM (1981), p. 105-110.	15, 16
Dynamic Young's Modulus parallel to bedding [MPa]	20500	23700	26900	Drillcore & sample	Derived from ultrasonic velocity measurements on drillcores. Method described in ISRM (1981), p. 105-110.	15, 16

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

ROCK MECHANICAL PARAMETERS (page 2 of 3)	Minimum value	Best estimate	Maximum value	Scale 1)	Method	Reference
Young's Modulus E1 [MPa]	7100	9500	11900	Drillcore&sample	Short-term laboratory testing, normal to bedding anisotropy. Confining pressure=0. Method described in DIN 4094-5 (2000).	16, 34
Young's Modulus E2=E3 [MPa]	11500	15500	19500	Drillcore&sample	Short-term laboratory testing, parallel to bedding anisotropy. Confining pressure=0. Method described in DIN 4094-5 (2000).	16, 34
Young's Modulus E1 [MPa]	2100	2800	3500	Borehole, field testing	Short-term field dilatometer testing, normal to bedding anisotropy. Method described in ISRM (1981), p. 132.	15, 16
Young's Modulus E2=E3 [MPa]	6300	7200	8100	Borehole, field testing	Short-term field dilatometer testing, parallel to bedding anisotropy. Method described in ISRM (1981), p. 132.	15, 16
Remark on elastic modulus: the large range of calculated E moduli is explained by the variability of rock strengths related to different water contents of the rock samples (see Figure AN 4-6 of the geological illustrations). The derived E moduli are dependent on the fabric anisotropy: E moduli derived from bedding-parallel stress-strain measurements are higher than those normal to bedding and the latter are higher than those oblique to bedding. Generally, the laboratory tests resulted in the highest E moduli, followed by the short-term dilatometer tests in boreholes. The smallest E moduli were derived from long-term dilatometer tests in boreholes, where small borehole deformations originating from pressure fluctuations were analysed.						
Poisson's Ratio v12=v13 [-]	0.16	0.24	0.32	Drillcore&sample	Short-term laboratory testing, parallel to bedding anisotropy. Method described in ISRM (1981), p. 116.	15, 16
Poisson's Ratio v23 [-]	0.28	0.33	0.38	Drillcore&sample	Short-term laboratory testing, normal to bedding anisotropy. Method described in ISRM (1981), p. 116.	15, 16
Shear Modulus G12=G13 [MPa]	800	1200	1600	Drillcore&sample	Short-term laboratory testing, parallel to bedding anisotropy.	16
Remark on transverse isotropic material: Opalinus Clay behaves as a mechanically transverse isotropic elastic material. This implies five independent elastic parameters: 1) E1 Young's Modulus normal to bedding, 2) E2=E3 Young's Modulus parallel to bedding, 3) v12=v13 Poisson's Ratio parallel to bedding, 4) v23 Poisson's Ratio normal to bedding and 5) G12=G13 shear modulus						
Cohesion (shear strength) [MPa]	2.2	3.6	5.5	Drillcore&sample	Parameters of the Mohr-Coulomb failure criterion. Method described in ISRM (1981), p. 123-127. See also DIN 18 137, part 2.	15, 16
Remark on cohesion: minimum value of 2.2 MPa: normal bedding. Maximum value of 5.5 MPa: parallel bedding. Shear strength of bedding planes is about 1 MPa						
Internal friction angle [°]	24	25	26	Drillcore&sample	Parameters of the Mohr-Coulomb failure criterion. Method described in ISRM (1981), p. 123-127. See also DIN 18 137, part 2.	15, 16

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

ROCK MECHANICAL PARAMETERS (page 3 of 3)	Minimum value	Best e-stimate	Maximum value	Scale 1)	Method	Reference
Swelling pressure normal to bedding (lab test) [MPa]	-	1.2	-	Drillcore&sample	Laboratory tests. Method described in ISRM (1981), p. 90-91.	15, 16
Swelling pressure parallel to bedding (lab test) [MPa]	-	0.5	-	Drillcore&sample	Laboratory tests. Method described in ISRM (1981), p. 90-91.	15, 16
Swelling pressure anisotropy (normal divided by parallel to bedding) [-]	-	2.4	-	Drillcore&sample		
Swelling strain normal to bedding (lab test) [%]	5	7	9	Drillcore&sample	Laboratory tests. Method described in ISRM (1981), p. 90-91.	15, 16
Swelling strain parallel to bedding (lab test) [%]	0.5	1	2.0	Drillcore&sample	Laboratory tests. Method described in ISRM (1981), p. 90-91.	15, 16
Swelling strain anisotropy (normal divided by parallel to bedding) [-]	4.5	7.0	10.0	Drillcore&sample		
Plastic limit [%]	-	-	-	-	Not applicable for stiff materials	-
Liquid limit [%]	-	-	-	-	Not applicable for stiff materials	-
Plasticity index [%]	-	-	-	-	Not applicable for stiff materials	-

1) Definition of scales: site scale 10-100 m, tunnel scale 0.1-10 m, drillcore & sample scale 1 mm-10 cm, micro scale < 1 mm.

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