INDUCED FRACTURING IN THE OPALINUS CLAY: AN INTEGRATED FIELD EXPERIMENT

S. YONG[1], S. LOEW[1], C. FIDELIBUS[1], E. FRANK[2], F. LEMY[1], and K. SCHUSTER[3]

[1] *Engineering Geology, ETH Zurich, Switzerland*
(*e-mail of corresponding author: yong@erdw.ethz.ch*)

[2] *Swiss Federal Nuclear Safety Inspectorate (HSK), Villigen, Switzerland*
[3] *Engineering Seismology & Ground Dynamics, Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany*

The Opalinus Clay is under consideration as a potential host rock for a nuclear waste repository in Switzerland. The performance of the repository may be affected by an Excavation Disturbed Zone (EDZ), which is inevitably created when an underground opening is constructed. A test niche was sequentially excavated and monitored in the Mont Terri Rock Laboratory, Switzerland, to obtain a description of the induced fracturing in the EDZ during and after the excavation and to identify the mechanisms that dominate their formation. The field investigation provides essential data for an integrated development of an experimental EDZ model that describes the *in situ* geological conditions, induced fracturing pattern, and rock mass response. The approach used in the field investigation is presented along with preliminary results.

Keywords: Rock; EDZ; Field Investigation; Opalinus Clay, Mont Terri.

1. Introduction

The safety of a nuclear waste repository depends strongly on the isolation properties of the host rock. Due to its low matrix permeability and the lack of tectonically disturbed zones, the Opalinus Clay has been selected as a potential host in Switzerland. The performance of the repository may be affected by an Excavation Disturbed Zone (EDZ), which is inevitably created when an underground opening is constructed. A reduction in the rock mass integrity results as the rock mass is dissected by induced fractures in the EDZ, which may increase the permeability of the rock mass in the near-field. The geometry and location of these induced fractures constitute an important issue in waste isolation.

At the Mont Terri Rock Laboratory in Switzerland (Fig. 1), several experiments have been carried out to characterize the EDZ in the Opalinus Clay (Bossart *et al.*, 2004 and Martin *et al.*,

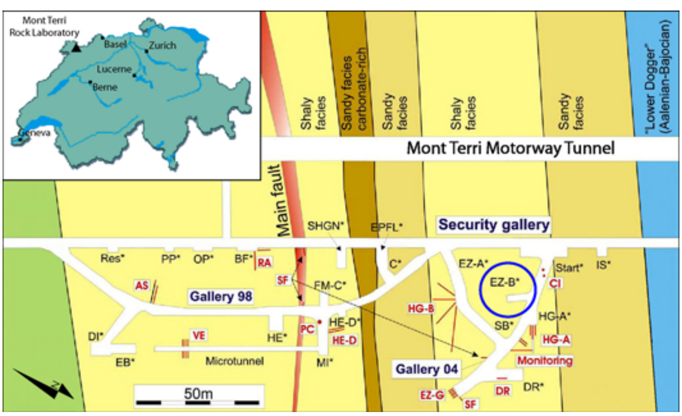

Fig. 1. The EZ-B experiment (circle) is located in the Mont Terri Rock Laboratory, Switzerland (inset).

2004). Structurally, the EDZ has been characterized as consisting of an inner zone and an outer zone. The inner zone is described as an interconnected network of induced fractures that is unsaturated and connected to the excavation. Conversely, induced fracturing in the outer zone is not necessarily interconnected or unsaturated, and the connectivity of this zone with the excavation is marginal. In addition, the intensity of induced fracturing in the EDZ has been found to decrease from the inner zone to the outer zone. The EDZ at Mont Terri has been attributed to swelling and softening, bedding plane slip, extensile fracturing, and stress-induced breakouts. All but the first are related to the stress redistribution incurred from the construction of an excavation. Previous studies postulate borehole breakouts and extensile fracturing occur during the opening construction while bedding plane slip occurs with time. Swelling and softening are time and moisture dependent processes that can also lead to bedding plane slip. Hence, induced fracturing in the Opalinus Clay at Mont Terri can be attributed to a number of individual processes and/or to a combination thereof, while the extent is dependent on the orientation of the opening relative to the bedding strike and the direction of the principal stresses, the excavation method and sequence, and the size of the opening.

Knowledge of the EDZ has widened substantially from research on the Opalinus Clay and at numerous research facilities akin to Mont Terri. Despite this, little is known about the influence of geological heterogeneities on the nucleation, propagation, and coalescence of the induced fractures; dominating mechanisms and factors; the timing of the formation; and three-dimensional effects. To gain insights in these areas, the EZ–B experiment was initiated at the Mont Terri Rock Laboratory. In the experiment, a test niche was excavated in a stepwise manner and the rock mass response monitored via surface and borehole methods. The main objectives are to describe the EDZ formation and to identify the factors and mechanisms that govern its formation. The key considerations are the geometry of the induced fractures and the network they encompass; the timing of the formation; and the influence of the excavation process, the pre-existing heterogeneities, the *in situ* stress field, and the atmospheric conditions. This paper focuses on the approach used in the field investigation and presents preliminary results.

2. Site Description

The field investigation was carried out in the new expansion (Gallery 04) of the rock laboratory, which is located in the Opalinus Clay (140m thickness) in the southern limb of the Mont Terri anticline. The Opalinus Clay is a Jurassic deposit consisting of a sequence of overconsolidated claystones and marls. Bedding planes at Mont Terri are highly continuous and thinly laminated with spacing <20mm (Martin *et al.* 2004). In the EZ–B niche, the bedding has a dip of ~44º and two major fault systems have been identified (Nussbaum *et al.* 2005). The shaly facies has an *in situ* water content of 6%, a plastic limit of 23% and a liquid limit of 38%. The uniaxial compressive strength is 16MPa perpendicular to bedding and 10MPa parallel to bedding while the elastic modulus is 4GPa and 10GPa, respectively. These values (Bock, 2001) illustrate the marked mechanical anisotropy caused by the bedding.

3. Field Investigation

The field investigation provides essential data for the development of an experimental EDZ model that describes the *in situ* geological conditions, the induced fracturing pattern, and the rock mass response. To facilitate detailed observations and measurements of the EZ–B niche EDZ, the field investigation was carried out in three stages: pre-, syn-, and post-excavation. The pre-excavation stage had a five-fold purpose: geological characterization, drillcore sampling for laboratory testing, pore pressure monitoring, provision of observation boreholes, and setting benchmark measurements for borehole monitoring methods. The syn-excavation stage focused on monitoring the EDZ development and evolution as the excavation advanced and also included characterizing the rock mass and documenting the influences of the experiment activities and excavation interruptions. In the post-excavation stage, the EDZ surrounding the niche was defined and its evolution monitored over timescales of weeks and months.

3.1. *Construction & Installation Activities*

Construction and installation activities consisted of borehole drilling, excavation, and the installation of instrumentation. A three-dimensional illustration of the construction is shown in Fig. 2 and the timeline is summarized in Fig. 3.

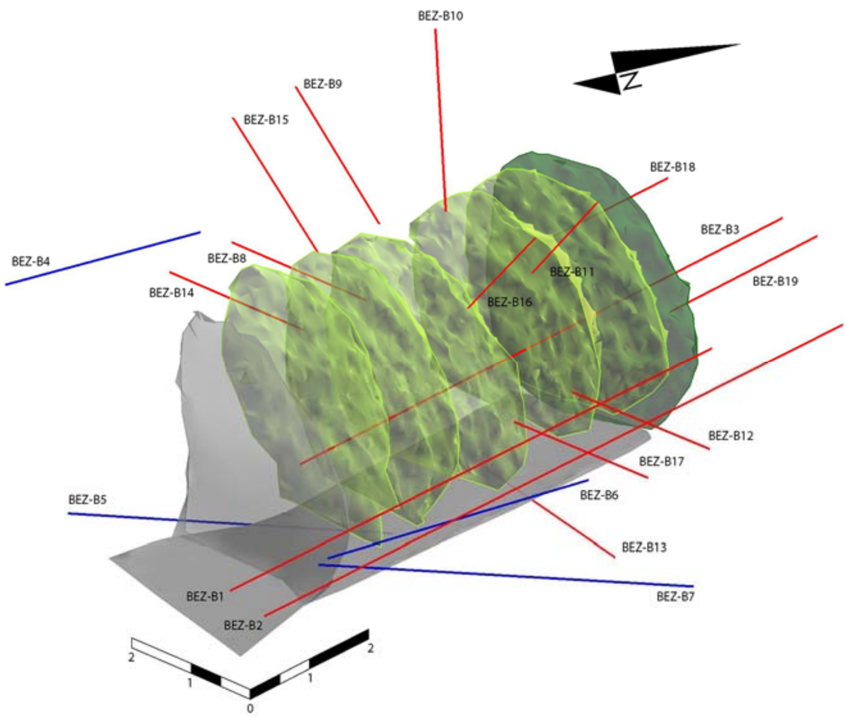

Fig. 2. An isometric view of the EZ-B niche construction and the borehole layout (drawing scale in metres). The entrance face is depicted in grey, the intermediary excavation steps in yellow, and the final face in green. The pore pressure boreholes are in blue and the observation boreholes in red. The top of the concrete floor is depicted in grey.

3.1.1. *Pre-excavation stage*

The pre-excavation stage spanned eight months and included the excavations of Gallery 04 in the vicinity of the EZ–B niche and its entrance and the installation of excavation support. Two sets of boreholes were drilled in this stage, four for pore pressure monitoring and three for geophysical observations. The pore pressure boreholes (BEZ–B4 to B7) were 20mm in diameter and located in different zones of pore pressure change. The observation boreholes (BEZ–B1 to B3) were 100mm in diameter and located in the area of greatest interest regarding the EDZ (i.e. the region immediately surrounding the excavation boundary). Thus, BEZ–B1 was located along the east

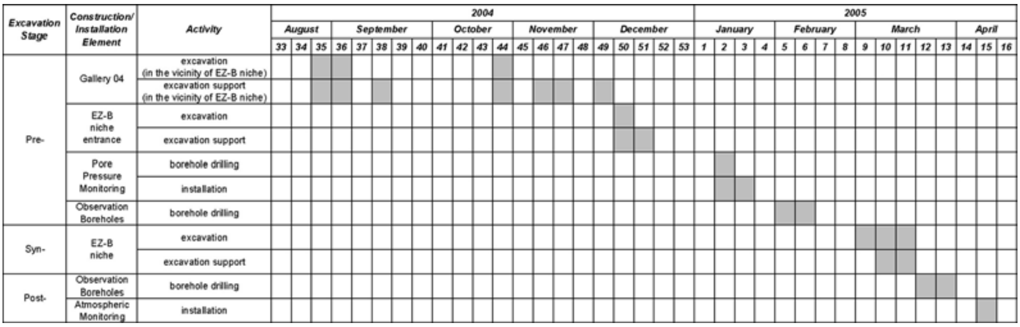

Fig. 3. The timeline and sequence of construction and installation activities in the field investigation.

wall of the niche and became the benchmark for the locations of BEZ–B2 to B3 and the alignment guide for the niche excavation. In turn, this required the partial excavation of BEZ–B1 as the niche advanced. BEZ–B2 and B3 were located no more than 2m from BEZ–B1 to be within the limits of effective seismic cross-hole measurements. In addition, the boreholes were not capped to ensure maximum borehole stability against the adverse effects of elevated humidity.

3.1.2. *Syn-excavation stage*

The niche (3.8m in diameter and 6.5m in length) was constructed with a pneumatic hammer in seven steps over a period of 12 days in the syn-excavation stage. The final niche face and body were created in the first six steps while the invert was excavated in its entirety in the last step. The first six excavation steps ranged from 0.3m to 1.3m. Each step except the first began with the excavation near the invert and concluded with the partial excavation of BEZ–B1. The first step was completed over a two-day period; the shotcrete lining was removed and a small opening in the entrance face was created on the first day, while the remaining rock mass was removed and the final cross-section shaped on the second day. Excavation support was also installed in this stage but only a minimum was required due to the advantageous orientation of the niche axis with the bedding. Roof support was installed intermittently during the first six steps and consisted of four overlapping steel mesh sheets attached with several aluminium nails and 24 steel anchors. The anchors were embedded ~50cm into the rock mass with an epoxy resin and were not tensioned. A 300mm thick concrete floor was poured over the invert and a 10cm thick foam contraction joint was incorporated in the centre of the floor to allow for movement at the base of the niche walls.

3.1.3. *Post-excavation stage*

The post-excavation stage began with the drilling of a third set of observation boreholes that radiated from the niche in three planes: two orthogonal to the niche axis and one parallel to it. The orthogonal plane closest to the face consisted of six boreholes (BEZ–B8 to B13) and provided the greatest radial coverage. The second orthogonal plane was drilled ~1m south of the first and consisted of four boreholes (BEZ–B14 to B17). The remaining boreholes (BEZ–B18 and B19) were drilled in the face at the same elevation as the pre-excavation boreholes (BEZ–B1 to B3) and located as close as possible to the sidewalls.

Borehole stability became an appreciable logging issue in this stage as four of the newly drilled boreholes (BEZ–B8, B14, B12, and B17) were oriented sub-parallel to bedding and thus, subjected to a higher propensity for collapse. Applying a vacuum was relatively effective at the beginning of this stage but over the subsequent months, an additional cleaning tool (similar to a garden spade) had to be incorporated.

3.2. *Field Measurements*

Several geological, geotechnical, geodetic, and geophysical measurements were carried out at each excavation stop, which ranged from 12 hours during the week to 65 hours over the weekend. Fig. 4 summarizes the data collected in each stage and indicates the number of datasets obtained.

Stage	Niche Mapping	Digital Video Documentation	Laser Scanner	Total Station	Tunnel Seismics	Atmospheric Monitoring	Drillcore Logging	Pore Pressure Monitoring	Optical Televiewer	Single-hole Seismics	Cross-hole Seismics	Spectral Gamma
	Surface						Borehole					
Pre	wall (1) face (1)						borehole (3)	continuous	borehole (3)	(3)	(2)	
Syn	wall, floor, roof (1) face (6)	continuous	(11)	(11)				continuous	borehole (18)	(11)	(6)	
Post			(1)	(1)	refraction (2) borehole (2)	continuous	borehole (12)	continuous	borehole (30)	(24)	(12)	borehole (15)

Fig. 4. A summary of the measurement activities in the field investigation with the number of datasets in brackets.

3.2.1. *Geology*

The geology of the rock mass will be characterized through the integration of geological maps, drillcore logs, optical televiewer images, spectral gamma logs, and seismic data. Subsequently, the spatial distribution and approximate size of significant geological heterogeneities will be determined. The focus of these measurements was the identification of significant pre-existing and induced features, such as lenses/inclusions, fault planes, and EDZ from Gallery 04 and the niche excavations (Figs. 5 and 6).

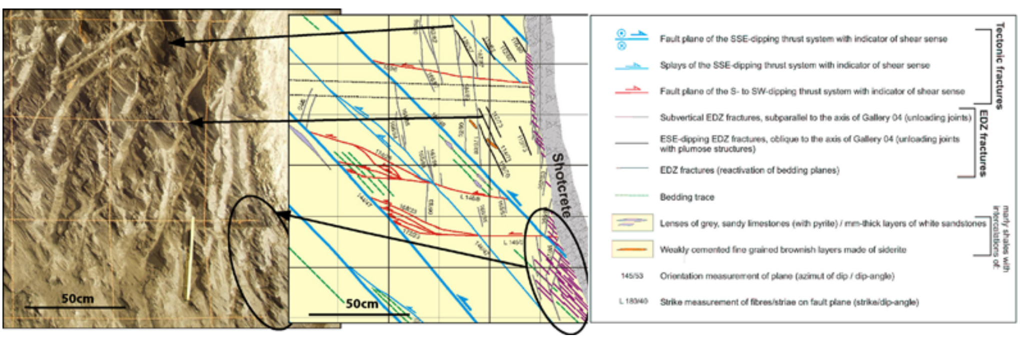

Fig. 5. Mapped EDZ fractures in the east wall of the EZ-B niche entrance (modified from Nussbaum *et al.*, 2005).

3.2.2. *Rock mass response*

The rock mass response will be characterized by integrating the pore pressure, displacement, seismic, and atmospheric data. Pore pressure and atmospheric data have been continuously recorded while displacement and seismic data have been periodically collected. Pore pressure sensors have been located 0.5–3m from the niche boundary while atmospheric sensors (temperature, humidity, pressure) were located in the niche interior. The niche excavation was also video-documented to provide assistance to data interpretation should the need arise.

Displacements were monitored by a novel approach, which incorporated point displacements measured with a total station and surficial displacements measured with a panoramic laser scanner. The total station method entailed installing and surveying discrete points as the

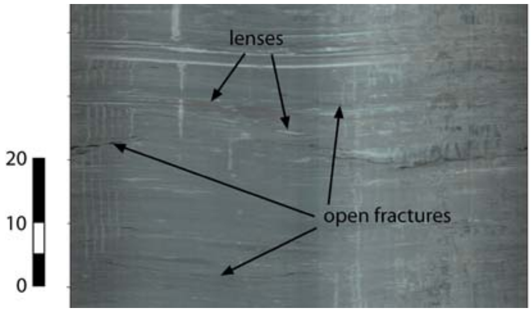

Fig. 6. Optical televiewer image (unwrapped) from a borehole drilled perpendicular to bedding. Sandy lenses and open fractures follow the bedding trace, which is subhorizontal. The scale is in centimetres.

excavation advanced. A total of 28 object points were installed over four circular arrays in the niche body and one linear array in the final niche face (Fig. 7a). Each circular array consisted of six points at 45° intervals that were aligned with the assumed directions of the principal stresses (Fig. 7a). The linear array consisted of three points distributed over the height of the final face. The laser scanner method consisted of scanning the niche surfaces and resulted in point clouds of x-, y-, z-coordinates (Fig. 7b). In the syn-excavation stage, 11 survey sessions were completed

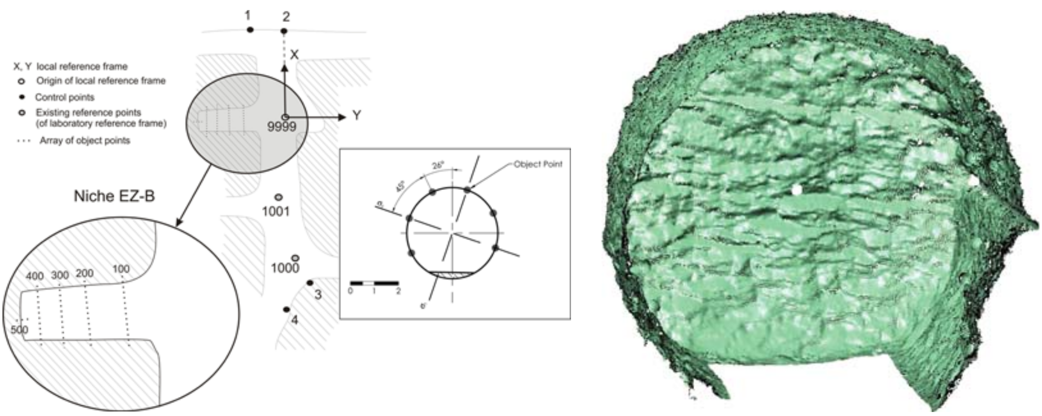

Fig. 7. The displacements were measured (a) at discrete points (inset) with a total station and along surfaces with a panoramic laser scanner via comparing point clouds (b). (modified from Lemy *et al.*, in press)

over a 12–day period, thereby encompassing three time-scales, hours, days, and weeks. The addition of a repeat measurement in the post-excavation expanded the time-scale to months.

Seismic measurements consisted of borehole and tunnel methods and have been carried out in 11 sessions. The seismic measurements began in the pre-excavation stage by establishing benchmarks, which consisted of seismic interval velocity in individual boreholes and cross-hole measurements between adjacent boreholes (Fig. 8). In the syn-excavation, the same measurements were carried out in the regions ahead of the face and those adjacent to the sidewalls. In the post-excavation, the investigation focused on completing the EDZ definition around the niche and monitoring its evolution via repeat measurements. The same single- and cross-hole measurements were made with the addition of tomography in a 1mx1m region in the east wall and tunnel seismics in the final face (Fig. 8). Tunnel seismics consisted of refraction measurements and borehole seismic profiling (i.e. a horizontal version of vertical seismic profiling) along two linear profiles aligned sub-parallel and perpendicular to bedding. In addition, interval velocity

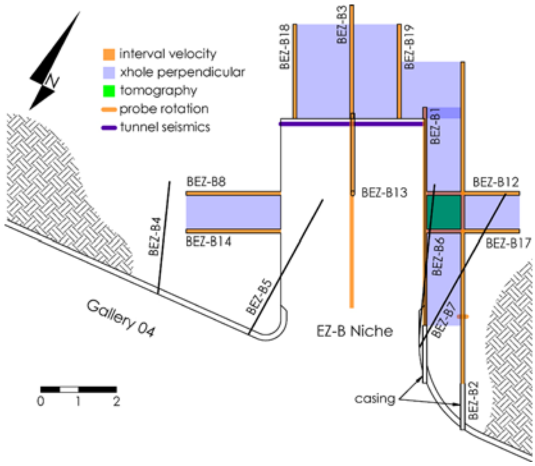

Fig. 8. Seismic measurements at the midheight of the niche (drawing scale in metres).

measurements with probe rotation were also made in BEZ–B2 in the pre- and post-excavation stages to assess the influence of the transmitting direction.

4. The Experimental EDZ Model

Preliminary results from the field investigation indicate complexity. Drillcore logs and televiewer images in the post-excavation boreholes showed little induced fracturing and few fractures cutting the bedding. Numerous EDZ fractures were identified in the niche entrance, whereas few were clearly identifiable in the niche interior. The seismic data showed a marked velocity increase ~1.5m ahead of the face and the pore pressure data showed suction in the floor and sidewall during the niche excavation. These observations indicate a need for integration of the collected data if the EDZ phenomenon in the EZ–B niche is to be understood.

Currently, integration of the field data is underway to develop an experimental EDZ model that will describe physical, mechanical, and temporal characteristics. The dataset in this research investigation is large and its integration complex. As a result, a number of tools are presently under development to ease and expedite the process. For example, data from the laser scanner (with a point cloud resolution in the order of mm's) is being processed through noise reduction and subtraction of spatial values to derive maps (Lemy *et al.*, in press) from which deformational patterns can be identified (Fig. 9). After processing, data will be integrated to produce a 3D visualization, thereby illustrating the spatial relationships and interactions between the datasets.

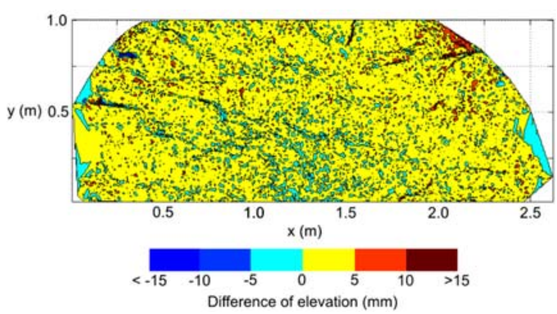

Fig. 9. A differential elevation map of the upper region of the final niche face that compares two laser scanning sessions six days apart (modified from Lemy *et al.*, in press).

For example, fault planes and EDZ fractures are being integrated with the location of the niche faces (Fig. 2) to define the relative geometry of the fracture network with the excavation interruptions. Likewise, the displacement vectors and differential elevation maps will be incorporated to correlate the fracture network with the deformational response. Subsequently, the experimental EDZ model will highlight areas that may require additional field investigations and isolate areas for numerical studies. The numerical studies will focus on identifying dominating mechanisms and factors responsible for induced fracturing around the EZ–B niche and facilitate an examination of the fracturing process via the application of fracture mechanics.

5. Conclusion

Induced fracturing in the EDZ constitutes an important issue in waste isolation. Describing the EDZ requires an integrated field experiment that involves the repeat use of complementary investigative methods. The EZ–B experiment utilized geological, geotechnical, geodetic, and geophysical methods to monitor the EDZ resulting from the stepwise excavation of a test niche in the Opalinus Clay at the Mont Terri Rock Laboratory. Preliminary results emphasize complexity in the EDZ: few induced fractures were clearly identified in the geological mapping while disturbance in the near-field during and after the niche construction were indicated by the pore pressure and seismic data. These observations indicate a need for data integration if the complex phenomenon of the EDZ is to be understood. Currently, data integration from the field investigation is underway, which will then facilitate the development of an experimental EDZ model. The experimental EDZ model will form a basis for the numerical studies necessary for identifying dominating EDZ mechanisms and factors and for examing the fracturing process via fracture mechanical concepts.

Acknowledgments

The authors acknowledge the Swiss Federal Nuclear Safety Inspectorate (HSK) for funding the EZ-B experiment and the following individuals for their valuable contributions: Hans-Joachim Alheid, Paul Bossart, Keith Evans, Urs Gerber, Peter Kaiser, Herbert Kull, Derek Martin, Marcel Mettler, Christophe Nussbaum, Christian Ris, Tilmann Rothfuchs, Jonas von Ruette, Thorsten Schulz, and Hans-Martin Zogg.

References

Bock, H. (2001). “RA Experiment Rock Mechanics Analyses and Synthesis: Data Report on Rock Mechanics”, Internal Technical Note, Federal Office for Water and Geology (FOWG), Berne.

Bossart, P., Trick, T., Meier, P. M., Mayor, J.-C. (2004). “Structural and Hydrogeological Characterisation of the Excavation-Disturbed Zone in the Opalinus Clay (Mont Terri Rock Project, Switzerland)”. *Applied Clay Science*, 26: 429–488.

Lemy, F., Yong, S., and Schulz, T. (in press). “A Case Study of Monitoring Tunnel Wall Displacement Using Laser Scanning Technology”. Proceedings of the 10th International Congress of the IAEG Copyright Geological Society of London, 6–10 September, 2006.

Martin, C. D., Lanyon, G. W., Bossart, P., Bluemling, P. (2004). “Excavation Disturbed Zone (EDZ) in Clay Shale: Mont Terri”, Internal Technical Note, Federal Office for Water and Geology (FOWG), Berne.

Nussbaum, C., Bossart, P., von Ruette, J., Badertscher, N., Meier, O. (2005). “EZ–B Experiment:

Small-scale Mapping of Tectonic and Artificial (EDZ) Fractures f the EZ–B Niche" , Internal Technical Note, Federal Office for Water and Geology (FOWG), Berne.