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Microstructure and composition of brittle faults in claystones of the Mont Terri rock laboratory (Switzerland): New data from petrographic studies, geophysical borehole logging and permeability tests

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ABSTRACT

Claystones are considered as a geological barrier. However, the properties of claystone may be modified if these are cut by brittle faults and fractures. Investigations of fault rocks are therefore crucial to evaluate the barrier properties of clay rich formations.

The present study is dealing with the characterization of naturally and artificially deformed Opalinus Clay of the Mont Terri rock laboratory in NW Switzerland. Complete core sections, covering the artificially excavation damaged zone (EDZ) and several tectonic fault zones, have been studied using a multidisciplinary approach consisting of geophysical, geotechnical, mineralogical/geochemical and lithological/structural data.

The fault zones encountered are characterized by a high density of planar discontinuities, which often show slickenside striations. Under the microscope, the fault zones turned out to be pervasively deformed resulting in open veins and pore space, now filled with calcite and celestine. Fault zone reactivation led to very fine-grained, cohesionless fault gouge and fragmentation of the previously formed calcite veins.

Packer tests in boreholes reveal excavation induced, enhanced permeabilities up to 3 m borehole depth (1.9 m ⊥ to gallery floor). Seismic borehole measurements indicate that seismic attributes, which are typical for undisturbed Opalinus Clay, are not reached until 7.5 m borehole depth (4.8 m ⊥ to gallery floor), which is larger than in the usual gallery configuration.

We interpret the anomalies in geophysical measurements as well as the elevated permeabilities, measured in the Main Fault (3.6 m to 4.2 m ⊥ to gallery floor), to result from an enlarged EDZ, influenced by the presence of the brittle fault structures. The up to two orders of magnitude higher permeability (compared to the intact claystone) most probably results from excavation induced stress and a local reactivation of fault planes.

The results suggest that the presence of a fault zone can alter the extent of the EDZ significantly, and thereby affect the rock integrity, at least in the near field of a repository tunnel.

1. Introduction

Investigations of fault rocks are crucial to evaluate the sealing properties of clay rich formations used as geological barriers for the storage of hydrocarbons or carbon dioxide gas or for the storage of heat generating radioactive waste. However, its sealing capability can be reduced if the claystones are cut by brittle faults (Lalieux and Horseman, 1998). Hydraulically active fault zones play an important role for fluid migration through the earth's crust and have the potential to control water, magma, hydrocarbon and hydrothermal flow (e.g. Caine et al., 1996; Faulkner et al., 2010 and references therein). Fluids may penetrate and influence rocks along fault zones even at depths of several kilometers (e.g. Nesbitt and Muehlenbachs, 1989; Zulauf et al., 1999; Boles et al., 2015). In this context, Caine et al. (1996) emphasized the need to continue the field based characterization in order to determine critical factors that control fluid flow in fault zones. Claystones are known effective top seals for hydrocarbon accumulations. For leakage to take place, tectonically induced, dilatant faulting and brittle fracturing must provide enhanced permeability (Ingram and Urai, 1999). Factors compromising the effectiveness of a potential claystone seal are fault displacements in excess of seal thickness, tensile fracturing under high fluid pressures and leakage via a network of juxtaposed leaky beds across sub-seismic faults within the seal (Ingram and Urai, 1999). From an engineering perspective, brittle fault zones in the

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meter- to dekameter-scale are considered as zones of mechanical weakness (Collettini et al., 2009), which represent major challenges for tunnel design and excavation work, requiring additional rock support (e.g. Nilsen, 2011).

In the present study, we used multiple geoscientific methods to study fault rocks exposed in the Mont Terri rock laboratory in NW Switzerland. We studied a complete drill core section crossing the Main Fault, which is a second-order thrust fault, branching off the basal décollement with a top-to-the NW displacement in the decameter-scale related to the development of the Jura fold-and-thrust belt (Nussbaum et al., 2011).

We used a comprehensive approach combining macro- and microstructural investigations of the drill cores combined with geochemical and phase analyses, seismic and electric borehole measurements, and hydraulic packer tests to determine the permeability and to reveal variations in the composition and barrier properties of both the claystones and the fault zones.

Our study is focusing on: (1) strain localization and characterization of heterogeneities in claystones using the above mentioned geological, mineralogical and geophysical methods; (2) the correlation of the data obtained; and (3) the impact of sedimentary and tectonic features (including the EDZ) on the permeability determined by in-situ packer tests.

The new data contributes to our understanding of the development, internal structure, and hydraulic properties of fault zones in claystones, and allows us to assess the influence of fault structures on EDZ development.

1.1. *Characterization of fault zones in claystone*

Since the classical experimental work of Riedel (1929), numerous studies have been carried out to constrain the deformation behavior and the mechanical properties of claystone (e.g. Nüesch, 1991; Chiarelli et al., 2000; Popp and Salzer, 2007; Zhang et al., 2007; Klinkenberg et al., 2009; Gräsle, 2011; Wild et al., 2017; Amann et al., 2017).

The relationships between pre-existing faults and excavation-induced damage were investigated during mine-by experiments at the Mont Terri rock laboratory by Yong et al. (2010, 2017) and Thöny (2014). The results are summarized in Amann et al. (2017). The relationship between fluid injection and fault displacement was investigated by a specially designed in-situ experiment, aiming at a reactivation of the Main Fault structure (Guglielmi et al., 2017). An injection pressure of ca. 4 MPa resulted in a transmissivity increase of several orders of magnitude, which is related to slip activation of the tested faults in the sub-millimeter range.

Hydraulically active fault systems in the rock laboratory Tournemire in SW France were studied by several authors (e.g. Bonin, 1998; Boisson et al., 2001; Cabrera, 2002; Dick et al., 2016). The Toarcian claystone of this domain is cut by numerous small scale fault systems, which are also influencing the Mesozoic limestone formations resting below and on top of the claystone. Some of the fault zones intersecting the tunnel are hydraulically active at a flow rate in the order of a few milliliters per hour (Bonin, 1998). The hydraulic conductivity ranges from $1E-14$ m/s in the intact rocks up to $5E-12$ m/s in the damaged area (Boisson et al., 2001; Dick et al., 2016). Faults are filled with calcite, but partially open cavities were also encountered (Cabrera, 2002). According to Bonin (1998), the solutions from which the vein material precipitated most probably originated from the adjacent marls and argillites.

Tectonic faults and fault zones cutting claystone of the Mont Terri rock laboratory were documented by Bossart and Thury (2008), Nussbaum et al. (2011) and Jaeggi et al. (2017). Three major fault systems have been found: (1) moderately SSE dipping reverse faults, (2) SW dipping low-angle faults, and (3) moderate to steeply dipping, N to NNE trending sinistral oblique-slip faults. Sealing of the tectonic fault surfaces with calcite fibers and the presence of swelling clay minerals in the fine-grained fault rock is, according to Nussbaum et al. (2011), the most probable reason for the lack of advective flow in these discontinuities. According to Nussbaum et al. (2011), the Main Fault in the rock laboratory forms a secondary fault structure, which branches off from the basal décollement. It ends presumably at the top of the Opalinus Clay and cannot be traced up to the surface. Palaeostress analyses revealed a subhorizontal orientation of the maximum principal stress, σ_1, trending NNW-SSE; the displacement is assumed to range in the decameter scale (Nussbaum et al., 2011). Microstructural investigations by Laurich et al. (2014) and Jaeggi et al. (2017) revealed three main structural elements in the Main Fault: deformed mm- to cm sized, lens shaped clay with a scaly fabric bounding the fault structure, a strongly deformed zone consisting of a fine grained fault gouge, predominant at the top of the Main Fault, and a rather undeformed central zone of rhombohedral blocks bound by individual fault planes with slickensides (see as well block model in Jaeggi et al., 2017). In addition, accumulations of calcite and celestine in form of veins and patches are occurring next to the tectonic structures. Laurich et al. (2014) report a reduction of the optically determined porosity ($< 1\%$) compared to the host rocks (varying from 8% to 24%). Overall, Laurich et al. (2014) argued that deformation in mudrocks is very localized, especially in the case of isolated slickensides.

The Federal Institute for Geosciences and Natural Resources in Germany (BGR) carries out in-situ permeability, ultrasonic and geoelectrical measurement in salt rocks, in granites and in claystones (rock laboratories Mont Terri and Grimsel, Switzerland, and the Meuse/Haute Marne site, France) using several specially designed borehole probes. Data from in-situ geophysical and geotechnical measurements concerning claystones as host rocks can be used for example for the characterization of the EDZ (Schuster et al., 2001; Kruschwitz and Yaramanci, 2004; Shao et al., 2008, 2016), and fracture-systems (Kunz et al., 2013) or for subsequent numerical THMC modelling (Kolditz et al., 2012; Yildizdag et al., 2014). Ultrasonic interval velocity measurements and the geotechnical instrumentation provide evidence for relevant changes in the elastic properties of profiles crossing the Main Fault and other minor fault zones (Thöny, 2014; Yong et al., 2013, 2017). The results indicate that artificial (excavation induced) fracture formation is controlled by the sedimentary anisotropy of the rocks as well as by the presence of pre-existing structures and faults, the latter forming mechanically weak zones. In this context, Thöny (2014) classified (amongst others) the following EDZ-structures: sub-horizontal extensional fractures parallel to the tunnel invert (IF3), extensional and/or shear fractures along bedding planes at the tunnel invert (IF4), extensional fractures subperpendicular to sheared bedding or reactivated fault planes (RF) at the tunnel invert (IF5).

1.2. *The Mont Terri rock laboratory*

The Mont Terri rock laboratory is located near the village St. Ursanne in NW-Switzerland (Canton Jura) within the Early to Middle Jurassic Opalinus Clay, an overconsolidated clay formation (Fig. 1). The rock laboratory is located within the Jura fold and thrust belt in the fold limb of the NW-vergent Mont Terri anticline. The development of the Jura fold belt began in the middle Miocene, ca. 12 Ma ago (Bolliger et al., 1993; Becker, 2000). The Mont Terri anticlinal structure evolved in a special tectonic setting at the crossing of several structural elements, such as the frontal part of the Jura fold belt (shortening direction NW-SE) and the roughly N-S trending Rhein-Bresse zone (for details see Nussbaum et al., 2011, 2017).

The thickness of the Opalinus Clay at Mont Terri is ca. 130 m (Hostettler et al., 2017), it dips approximately 40° towards SE. The thickness of the sedimentary cover varies between 230 m and 320 m, depending on the position inside the rock laboratory. At the drilling site of the borehole BSO-37, the overburden is ca. 270 m. The Opalinus Clay at Mont Terri can be divided into three distinct facies types (Thury and Bossart, 1999; Bossart and Thury, 2008; Lauper, 2016; Hostettler et al.,