Microstructural evolution of an incipient fault zone in Opalinus Clay: Insights from an optical and electron microscopic study of ion-beam polished samples from the Main Fault in the Mt-Terri underground research laboratory

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highly polished slickenside with nano-sized clay particles

thin, non-porous shear zone (< 4 μm)

calcite and celestite veins and calcite enriched patches

branch lines

tool tracks

light coloured spots (due to underlying calcite / celestite)

gouge

3 cm

scaly clay
Microstructural evolution of an incipient fault zone in Opalinus Clay: Insights from an optical and electron microscopic study of ion-beam polished samples from the Main Fault in the Mt-Terri Underground Research Laboratory.

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Abstract

Slickensided shear surfaces are ubiquitous in many fault zones. However the internal structure, the micromechanics and the evolution of these structures are not fully understood and the contributions of crystal plasticity, grain-boundary sliding, microfracturing, solution-precipitation and mineral transformation under different conditions are subject of debate.

We studied well-preserved core samples from the Main Fault, an up to 3 m wide zone of approximately 10 m offset in the Mont Terri Underground Research Laboratory (CH), a site to evaluate long-term safety of radioactive waste disposal. The drill core breaks easily along many slickensided shear surfaces indicating reverse slip, which form an anastomosing network connected by branch lines.
Broad ion beam polishing and scanning electron microscopy shows that the slickensides are invariably revealed by fracture of the drill core along a few µm thick shear zone, which acts as a crack guide for fracturing the samples. In this zone, a complex set of processes is inferred, leading to extreme localization of strain, development of strong particle preferred orientation, the formation of nanoparticles, and local precipitation of calcite veins in releasing sections. In lenses between shear zones, homogeneous gouge is formed with a well-developed oblique foliation and removal of calcite grains by pressure solution. We infer that with progressive deformation, the number and density of slickensided shear surfaces increases, generating tectonically derived scaly clay and more homogeneous gouge. In all deformed elements of the Main Fault, porosity is much smaller than in the undeformed Opalinus Clay. An interesting observation is the almost complete absence of cataclastic microstructures. Transmission electron microscopy (TEM) of focused ion beam lamellae of this micron-wide shear zone shows a strong preferred orientation of clay minerals, including nano-sized illite particles. In TEM, the shear zones envelop hard particles and confirm an almost complete loss of porosity compared to the protolith.

We propose that inter- and transgranular microcracking, pressure solution, clay neoformation, crystal plasticity and grain boundary sliding are important micro-scale processes during the early stages of faulting in Opalinus Clay and thus need to be considered in extrapolating laboratory results to long-term mechanical behavior.

1 Introduction

Incipient tectonic deformation in compacted clay-rich sediments is usually highly localized in thin shear zones (deformation bands) (Agar et al., 1989; Dehandschutter et al., 2005; Ishii, 2012; Labaume et al., 1997; Milliken and Reed, 2010). With progressive strain, the density of these
shears increases and they form clusters (e.g. Rutter et al., 1986; Logan et al., 1992; Haines et al., 2013). While the geometries of these shear zones can be similar, the micro-scale mechanisms of deformation can vary widely (e.g. Rutter et al., 1986), and the interplay of crystal plasticity in clays (Urai and Wong, 1994), particle reorientation and pore collapse (Morgenstern and Tchalenko, 1967; Milliken and Reed, 2010; Haines et al., 2013), grain-size reduction (Bos and Spiers, 2001; Mitra and Ismat, 2001; Rutter et al., 1986), solution-precipitation and grain-boundary sliding and mineral transformation (Boullier et al., 2009; Buatier et al., 2012a; Gratier et al., 2011; Haines and van der Pluijm, 2012; Sasseville et al., 2012; Schleicher et al., 2006; Warr and Cox, 2001) are all subjects of debate.

Samples broken along these thin shear zones usually show slickensides, with a smooth, shiny striated surface (*sensu* Passchier and Trouw, 2005). Slickensides are common in both experimentally and naturally deformed samples of many materials and have been studied by Doblas (1998), Gay (1970), Means (1987), Petit and Laville (1987) and Tjia (1964) and in clays by Dehandschutter et al. (2005), Gray and Nickelsen (1989), Labaume et al. (1997), Saffer et al. (2012) and Will and Wilson (1989).

While the extreme localization of strain in a hierarchy of shear zones is generally recognized, the use of the terms “slip surface”, “shear plane” and “thin slip zone” tends to differ between authors, and is scale dependent (e.g. Nussbaum et al., 2011; De Paola, 2013; Fondriest et al., 2013). Study of the grain-scale deformation mechanisms in these zones is complicated by the very fine grain size and fragile fabric (cf. Vrolijk and van der Pluijm, 1999), which makes sample preparation and analysis difficult. In recent years, ion-milling techniques have led to a breakthrough in sample preparation of clays, and to renewed interest in microstructural study (e.g. Holzer et al., 2006; Desbois et al., 2009, 2010, 2011). While the porosity and microfabric of tectonically
undeformed Opalinus Clay (OPA) have been intensively studied (Houben et al., 2013; Keller et al., 2011; Wenk et al., 2008), little is known of the microstructure and deformation mechanisms in naturally and experimentally deformed OPA.

This contribution reports an investigation of microstructures in naturally deformed OPA from the Main Fault at the Mont Terri Underground Research Laboratory (MT URL, Figure 1). We present microstructural data at scales ranging from dm to nm, obtained by light and electron microscopy. Based on these data, we discuss deformation mechanisms in our samples, focusing on incipient faulting, the early evolution of fault gouge, and processes for resealing fluid pathways.

1.1 Geology

As its main objective, the MT URL evaluates the long-term safety of radioactive waste disposal by basic and applied research. A detailed description on the local geological setting can be found in Nussbaum et al. (2011), in Bossart and Thury (2008), and in Becker (2000). The Main Fault, a 0.8 - 3 m wide fault zone exposed in the MT URL with a reverse offset of about 10 m, provides an excellent opportunity to investigate incipient faulting in mudrocks, because of the unique access to extremely well preserved samples and the large dataset of geochemical, structural and hydrological studies (e.g. Pearson et al., 2003; Bossart and Wermeille, 2003; Nussbaum and Bossart, 2008). Of this extensive database, the following aspects are particularly relevant for this study:

(1) The protolith (sensu Rutter et al., 2001) is the shaly facies of OPA, which consists mainly of clay minerals (16 - 40 % illite and 5 - 20 % mixed-layer illite-smectite, 15 - 33 % kaolinite, 4 - 20 % chlorite), 5 - 28 % calcite (fossils and minor veins) and 6 - 24 % quartz (Pearson et al., 2003). The tectonically undeformed fabric is heterogeneous and
weakly foliated along bedding, with a porosity of 8 - 24 % (Houben et al., 2013; Nussbaum and Bossart, 2008).

(2) The detailed fracture network and strain intensity within the zone of the Main Fault is heterogeneous (Nussbaum et al., 2011), comprising zones with fault gouge, C'-type shear bands (sensu Passchier and Trouw, 2005), meso-scale folds, microfolds, numerous fault planes and apparently undisturbed parts (Figure 2). Parts of the Main Fault (e.g. the upper part of the outcrop in Figure 2) comprise a ‘scaly’ fabric, where the rock splits progressively into smaller fish-like flakes (sensu Vannucchi et al., 2003).

(3) P-T conditions at the time of the onset of motion of the Main Fault (late Miocene, Nussbaum et al., 2011) are inferred by Mazurek et al. (2006) to be about 55 °C under an overburden of 1000 m, using an integration of apatite fission track, vitrinite reflectance and biomarker isomerization analysis. The maximum overburden and temperature of OPA at MT URL was 1350 m and 85 °C, respectively, during Cretaceous times (Mazurek et al., 2006). Thus, OPA, which now has a strongly anisotropic unconfined compressive strength between 6 and 28 MPa (Amann et al., 2011; Bock, 2001), was over-consolidated at the onset of faulting.

(4) The kinematics of the Main Fault have been inferred by paleostress analysis of slickenlines (Figure 2), showing $\sigma_1$ to be sub-horizontal, trending NNW-SSE for a reverse faulting mode (Nussbaum et al., 2011). This geometry agrees with the „distant push“ or „Fernschub“ theory of the Jura folding as a consequence of the propagation of the Alpine foreland towards NNW (Laubscher, 1961). The Main Fault can be interpreted as a shear fault-bend fold (Nussbaum et al., 2011), which was passively steepened from 20° to the range of 40° - 45° in sequence with the folding of the Mont Terri anticline over
a basal ramp (Figure 1). From area balancing (Freivogel and Huggenberger, 2003), the offset of the Main Fault is inferred to be relatively small (~ 10 m).

(5) The paleo-fluid flux within the MT URL has been inferred from calcite (CaCO₃) and celestite (SrSO₄) veins (Pearson et al., 2003). In a recent, comprehensive study, de Haller et al. (2014) presented detailed petrographic and geochemical data about veins in the Main Fault. Veins were found as thin (< 1 mm thick) wafers of calcite and celestite, with fibrous crack-seal microstructure, indicating syntectonic precipitation. Based on isotope data (Sr, S, O, C), de Haller et al. (2014) suggested that OPA acted as a seal for fluid flow during most of its history except during the movement of the Main Fault. The present permeability of OPA is very low with no significant hydrological contrast between protolith and the Main Fault (~2 x 10⁻¹³ m/s, (Nussbaum and Bossart, 2008). Profiles of a range of pore-fluid geochemical tracers are not perturbed near or within the Main Fault (Mazurek et al., 2011).

2 Samples and Methods

Drill cores from five boreholes in the fault zone (BSF-06, BPS-10, BPS-11, BPS-12 and BIC-A1, see Figure 1 for location), up to 50 m apart, were collected. Considering the extremely fragile nature of fault zones in clays, these cores were collected by drilling into the walls and floor of the MT URL, with air as lubricant and careful core extraction. Dip and reverse faulting mode of faults and slickenlines are in agreement with outcrop investigations by Nussbaum et al. (2011). Strike orientations were not verifiable, as the drill cores were not oriented. The cores BSF-06, BPS-10 and BPS-11 were taken by a resin stabilized coring procedure (details in Nussbaum et al., 2006). Despite the care during drilling, the non-stabilized cores BPS-12 and BIC-A1 broke into pieces of up to 30 cm in length, along shiny, wavy surfaces with striations (i.e. slickensides,
Figure 3). Although undeformed OPA produces quite strong and intact drill cores, the collected core fragments easily broke along fractures with slickensides.

Preparation (dry) for this study used sample blocks of a few cm on each side, cut from the core, which was resin-stabilized if required, with a low speed diamond saw. The samples have either (1) a slickenside exposed on one side or (2) a slickenside inside the block with the slickenside parallel to one side (Figure 2C). The samples were investigated by optical and electron microscopy in surface view (A) and in side view (B). In the latter case, a surface perpendicular to the slickenside and parallel to the slickenlines was examined (Figure 4). Here, the samples were further prepared by five different methods: (i) breaking perpendicular to the slickenside and parallel to the slickenlines, guided by a pre-cut, (ii) hand-polishing of large (10 x 10 cm) surfaces followed by immersion in water for one second and drying to decorate foliation and shear zones, (iii) ultra-thin sectioning (prepared by Geoprep, Basel), (iv) hand polishing followed by broad ion beam (BIB) polishing, and (v) cutting transmission electron microscopy (TEM) lamellae by focused ion beam (FIB) (Figure 2C).

Argon BIB polished sections of about 2 mm² were prepared using a JEOL SM 09010 (8.5 h at 6 kV, 150 - 200 mA, 10^-3 - 10^-4 Pa). This process removed a layer about 100 µm thick from the pre-polished surface using the methods described in detail by Houben et al (2013). The BIB polished, damage-free and flat (+/- 5 nm, Klaver et al., 2012) surfaces allow detailed imaging of microfabric and pores. To prevent curtaining and edge effects, the slickensides were covered by gluing a 0.15 mm thick glass plate on the surface with epoxy resin before polishing (Figure 4).

Scanning electron microscopy (SEM) was performed on a Zeiss SUPRA 55 operating between 3 and 20 kV, using a backscattered electron detector (BSE) and a secondary electron detector (SE), respectively. Further, an energy-dispersive X-ray (EDX) detector (at 15-20 kV) was used.
With these detectors, the depth in the sample from which information is provided is up to about 2 µm for the different detectors and acceleration voltages.

Following the procedures of Desbois et al. (2010), Houben et al. (2013), Klaver et al. (2012) and Hemes et al. (2013), semi-automated digital image analysis (DIA) was performed on high-resolution mosaics of up to 400 single SE micrographs with magnifications up to 30 kx. This approach provided segmented pores used for subsequent statistical analysis of size distribution, shape factors and orientation. Moreover, spatial distributions of these porosity parameters were mapped. For each cell of a computed grid with a cell size of 1 * 1 µm², porosity, pore orientation and pore shape factors were calculated and each cell was colored accordingly (using ArcGIS 10, ESRI 2013). The chosen cell size, being in the range of clay particles, gave the most practical spatial information.

For nm-scale investigation of the zone directly underlying the slickenside, TEM was used to image FIB lamellae of 10 x 5 µm² and 100 to 150 nm thick (FIB: Strata 205, FEI, Central Facility for Electron Microscopy, University of Aachen, tungsten coating, 30 kV, 20 nA – 100 pA; TEM: Zeiss Libra 200FE operating at 200 kV, Koehler illumination system, Institute for Mineralogy, University of Münster). High angle annular dark field (HAADF) scanning TEM (STEM) and bright field (BF) images were collected, giving information on average atomic number and mainly diffraction contrast, i.e. crystallinity of illuminated areas, respectively. EDX measurements with short dwell times were used to minimize sample damage. Selected area electron diffraction (SAED) patterns were recorded to specify major element characteristics and crystallographic parameters of regions of interest within the lamella.

All procedures were applied under fully dry conditions in air (except the water immersion - these samples were not used for further analysis). Previous SEM studies on Boom Clay and OPA
(Dehandschutter et al., 2005; Houben et al., 2013) reported that slow sample drying under atmospheric conditions will result in similar minor microstructural artifacts as other drying methods, producing bedding-parallel cracks with undisturbed matrix between the cracks.

3 Results

At our scale of observations, the structural elements were consistent between samples from different drill cores, so the results shown here are described as representative for the Main Fault, and illustrated with select examples.

We observe the following structural elements: (1) slickensides (Figure 3), which are in cross-sectional view associated to (2) a thin zone of slickenside parallel oriented particles, (3) gouge, (4) calcite and celestite veins (Figure 7) and (5) scaly clay (Figure 16). Gouge is rare while the other elements are common in the Main Fault. The same structural elements were distinguished in the fault core and damage zone of the Main Fault (drill cores BSF-04, BSF-06, BSF-11 and BSF-12) by de Haller et al. (2014), and at the macro- to micro-scale, our observations are fully consistent with the data presented in that study.

3.1 Surface view - Slickensides

We use the term slickenside for the shiny, striated surface seen on broken core pieces. The surface structure of slickensides shows differences in step length, step height, shininess and orientation to bedding. In the MT URL, the angle between the Main Fault zone and bedding is about 15 to 25 degrees and in our samples the angle between slickensides and bedding foliation can vary between 0 and 45 degrees (Figure 3). Commonly, the step length is larger for slickensides parallel to bedding, however exceptions occur (Figure 3D).
At optical resolution, each slickenside consists of matt, ragged areas and shiny, flat, polished areas, which show slight brightness and color variations (Figure 3A). By stereo microscopy, a few occurrences of asymmetric cavities, crescent-shaped markings and trailed material were detected, all in agreement with reverse motion, such that the steps are congruous to shear sense (after the terminology of Doblas, 1998). We found no offset markers to allow measurement of displacement because this part of the Shaly Facies is rather homogeneous without laminations that could be used as markers. Based on a grain trace, the offset for one wide-stepped (~ 3 cm) slickenside was determined to be at least 1.6 cm (Figure 3B). Curved fractures outcropping on a slickenside, sometimes with a riser, were usually shown to be branch lines (sensu Walsh et al., 1999) of intersecting slickensides (cf. Figure 4). The vast majority of striae resemble the continuous ridge-in-groove type described by Means (1987), located next to risers, usually thinning out along the steps (Figure 3).

At SEM-scale, zoom-in sequences in Figure 5 and Figure 6 compare the surfaces of narrow- to wide-stepped slickensides. The wide-stepped slickenside has a smoother, less striated surface. For scales of 100 µm and smaller, however, slickensides do not differ much, and show at high magnifications particles of 200 nm and less, surrounding larger particles (Figure 5C and F, Figure 6C). In BSE images of a slickenside, brightness variations are interpreted as minerals with a higher atomic number directly underlying clay particles (Figure 5E). Even at the limit of resolution of SEM (up to 100 kx magnification), porosity is not resolvable on these surfaces and the slickensides appear as the surface of a continuous, smooth, non-porous film covering underlying OPA. Occasionally, subeuhedral calcite and celestite crystals are associated with risers (Figure 6). In BSE images, calcite and celestite lineations can be seen on some slickensides (Figure 6).
3.2 Side view

3.2.1 Thin zone underlying slickensides

Figure 7 shows a transmitted light micrograph of an ultra-thin section from sample BIC-A1-UTH6, with an open fracture that exposes slickensides on both fracture surfaces (shown in surface view in Figure 3D). The fracture walls nest, indicating that no material fell out from between them during later fracture opening. The image was taken with crossed polarizers and gypsum plate, with the blue color showing the bedding-parallel preferred orientation of clay particles of undeformed OPA.

On both sides of Figure 7A, a zone of higher order colors indicates enrichment of calcite in a 50 µm thick vein (Figure 7C). On the left side of the image, a fish-shaped zone is defined by sharp boundaries where the preferred orientation makes an angle with bedding foliation and seems to contain less of the bright calcite grains than the surrounding protolith (Figure 7B). At the interface between both fracture walls, a few µm wide zone, barely visible by light microscopy, differs from the surrounding material by color (Figure 7D). The zone suggests a different preferred orientation than the protolith. In BSE imaging, this zone is darker, and more fine-grained, with a trace of an oblique foliation (note that this image was taken on a surface which has been mechanically polished during preparation, and is not as smooth and damage-free as a BIB-polished surface).

The few micron-wide zone is present immediately below all investigated slickensides. Figure 8 shows SE images of a surface, broken perpendicular to a slickenside in sample BIC-A1-U10. Here, the undeformed OPA fabric is truncated by a sub-micron thick film showing a stacked sheet of overlapping platy clay particles that wrap around a fossil grain.
Another illustration of this microstructure is shown in Figure 9 (BIB-SEM sample BIC-A1-S9). Next to the slickenside surface, an up to 3 µm thick zone is visible, with an internal microstructure of slickenside-parallel-oriented clay particles enveloping a pyrite grain that slightly protrudes out of the slickenside. The amount of porosity of this sample is comparable to undeformed OPA (19 vs. 18 - 23 %, cf. Houben et al., 2013) and lacks any trend in porosity, pore shape or pore orientation up to the thin zone next to the fracture (Figure 9C and E). The thin zone, however, shows almost no porosity at SEM resolution (Figure 9D and F). For imaging purposes, the sample was prepared by gluing a glass plate on the slickenside before BIB polishing and epoxy could have filled pores in the thin zone, so the next example shown is without epoxy.

The absence of porosity in a thin zone is also visible in BIB-SEM sample BIC-A1-U2 (Figure 10). Here, an open, not epoxy filled fracture (possibly revealing slickensides on both fracture walls) separates the thin zone of aligned clay particles. Larger particles of calcite, quartz and pyrite framboids are never truncated by the fracture walls. The thin zone is up to 2.5 µm thick, with almost no pores visible by SEM. A rare example of a tabular particle (mica) bent into parallelism with the slickenside is shown by the arrow (Figure 10A).

The thin zone underlying the slickenside is examined in greater detail in lamella TEM1 (Figure 11), which was cut from the slickenside shown in Figure 5B. Therein, the ~1 µm thin zone consists of densely stacked clay particles, which are aligned (face to face texture) parallel to the slickenside (Figure 11B). By SAED and HRTEM, clay particles next to the slickenside were identified as illite, with a lattice spacing of 10Å (=d_001) (not shown). By STEM (HAADF), quartz grains close to the slickenside are found to be enveloped by bent illite grains (Figure 12). The presence of nm-sized illite particles corresponds to the top-view observations presented above.
Figure 12B sketches the interpreted microstructure for this image, highlighting that the few small pores next to the slickenside are of inter-particle type and mainly related to pressure shadows of quartz grains. At the same time, the finite thickness of the TEM lamellae causes the apparent porosity to be greater than seen on a 2D surface, (Krabbendam et al., 2003).

In summary, FIB-TEM results agree with our BIB-SEM observations of a strong porosity reduction in a zone next to the slickenside with a strong preferred orientation and the presence of nanoparticles. Also, the grains in this zone and in this sample are illite, suggesting that these zones can be locations of illite neoformation. The transition from undeformed OPA into this zone is invariably sharp, and occurs over a few 100 nm.

3.2.2 Gouge

In Figure 7A and B, we showed an example of the wider bands or lenses of deformed material between some of the shear zones defining the slickensides. In this section, we describe these bands or lenses in more detail. The ultra-thin section BIC-A1 UTh3 (xpol, gypsum plate), has a few micron-wide zone branches enveloping a 2 mm wide gouge lens (Figure 13A). In this material, the preferred orientation makes an angle with the foliation of the protolith, and the gouge contains less of the bright calcite particles than the protolith.

Sample BIC-A1-UTHB4, similarly shows continuous gouge over several cm, with a clearly lower content of bright calcite grains, a sigmoidal foliation curving into parallelism with the lens boundary, and a darker color in parallel polarizers (Figure 13B). The gouge thickness varies between 2 and 0.2 mm, being limited by one almost straight and one irregular boundary to the protolith (Figure 13).
A similar gouge lens is found in borehole BIC-A1 (Figure 14). This sample was cut in two halves (BIC-A1-Th3 and BIC-A1-U8) with a thin diamond saw, one half used for thin section and the other half (showing the same microstructure) for BIB-SEM analysis, locating the 1 mm\(^2\) of the BIB section to cover undeformed OPA, gouge and a section of undisturbed contact (generally, gouge lenses easily separate from protolith along slickensides). At the gouge - protolith boundary, elongate particles are parallel to the boundary (Figure 14D), while in the gouge (Figure 14C) there is a foliation in P-orientation (sensu Logan et al., 1979). At the boundary, a 1 - 2 µm thin zone of nm-sized, boundary-parallel clay particles discordantly covers the wall rock (Figure 14D). The gouge shows a clear decrease in grain size and an increase in fabric intensity compared to the protoliths’ fabric (Figure 14C, Figure 9A). Particle sizes in the gouge are less than 25 µm (usually less than 5 µm) in diameter, rounded and elongated and aligned along the gouge foliation (Figure 14C). The clay matrix shows a strong preferred orientation anastomosing around more competent grains. Many particles are at the resolution limit of BSE imaging. EDX mapping only resolves a change in composition between protolith and gouge for a reduction in Ca due to the absence of large calcite grains (mainly fossils) in the gouge (e.g. Figure 14B). Shear bands occur occasionally, defining an S-C fabric in the gouge (Figure 14E). In a few cases, trans-granular cracks are visible in the larger grains, with crack porosity and clay filling in the crack (Figure 14F).

Segmentation of pores in SE images from the gouge shows a porosity of less than 1 % of inter-particle pores. This porosity is much less than in undeformed OPA (8 - 24 %, Houben et al., 2013). The majority of pores within the gouge are elongated, with larger pores being more elongated than smaller ones. The orientations of the pores’ longest axes are unimodally distributed and their mean orientation is in agreement with the minerals’ P-orientation.
3.2.3 Veins and zones of calcite enrichment

In both optical microscopy and BIB-SEM, veins of calcite and sometimes celestite and zones of grain-scale calcite enrichment were found, always located directly at the slickensides, both along the thin zones and the gouge-protolith contact (e.g. Figure 7, Figure 15). Veins are thinner than 1 mm, commonly less than 0.1 mm thick. As shown above in surface view, calcite and celestite are occasionally associated with risers and sometimes form slickenfibre veins (sensu Passchier and Trouw, 2005)(Figure 6A). This relationship is consistent with the observations in side view: the BIB-SEM image of BIC-A1-U5 in Figure 6F-G shows a thin clay layer separating two calcite-celestite mixed veins. Such a vein texture is described by Passchier and Trouw (2005) as a striped shear vein with the clay layer as an inclusion trail. The inclusion trail itself can be a slickenside (cf. Stanley, 1990). From BIB-SEM, the porosity in veins is very low. The fine grain size of the veins prevents clear imaging in optical microscopy, but in BSE imaging (Figure 15E and F), the veins are shown to be laminated and, as the inset in Figure 15A illustrates, contain grains elongated in the direction of the vein (cf. Koehn and Passchier, 2000). Usually the fracture exposing the slickensides runs along the contact protolith - vein on one side, but in some cases also internally, exposing a vein on both sides of the fracture (Figure 15A). Locally, the vein tip bends away from the slickenside, terminating in the protolith (arrow in Figure 15B). Veins usually have at their boundary a thin shear zone (clay), which positions the veins underneath the slickenside and which can occasional separate veins (Figure 6C).

The zones of grain-scale calcite enrichment are generally associated with the veins, but can also be present at risers in the slickenside (Figure 15C and D). These zones consist of a mixture of irregular- shaped calcite grains, sometimes showing zonation in BSE, mixed with fine- grained clay fragments.
These observations are consistent with data from de Haller et al. (2014), who studied vein fragments extracted from disintegrated samples of the Main Fault. We show that the veins are always closely associated with slickensides, and form thin patches along these surfaces.

3.2.4 Scaly Clay

Parts of the outcrop shown in Figure 2 and drill cores BIC-A1 and BPS-12 show zones of ‘scaly’ fabric (Figure 16). These zones range in width from several cm up to ca. 1 m. There, the rock is separated into progressively smaller fish-like flakes down to less than 300 µm in diameter, each of which is bound by slickensides. In this contribution, we present a first look at a small number of these flakes, embedded in epoxy and polished by BIB. The samples studied so far contain an internal fabric similar to the protolith, intersected with incipient shear zones (Figure 17). The rim of the flake shows a 1 - 2 µm thin zone of parallel oriented clay particles, similarly found in thin zones underlying slickensides from the non-scaly clay part of the outcrop. More work is needed to test if this is representative for all scaly clay in the Main Fault, but these data provide a first impression that the scaly clays are defined by a higher density of shear zones, and not by internal deformation of the flakes resembling microlithons.
4 Discussion

The outcrops of the Main Fault in the MT URL provide a unique opportunity to study exceptionally well preserved samples recording the early stages of faulting in a slightly indurated claystone. Timing and conditions of the faulting are reasonably constrained and to date the fault zone is known to have a permeability as low as the surrounding protolith. Motion of the Main Fault could be associated with small seismic slips, triggered in the hard Triassic dolostones below or by stress changes during motion of the basal thrust, and followed by the much weaker OPA.

Of the structural elements described in this paper, Figure 18 summarizes the main features in a generic model. Slickensides are the main structural element in the samples studied. It is commonly agreed that they were formed by localized shearing of the protolith in many lithologies and under a range of conditions. From our observations at the sub-micron scale slickensides are similar in morphology in the Main Fault. They are revealed by fracturing of the sample during or after extraction from the drill core along zones with a very strong preferred orientation of fine grained clay. These zones are ubiquitous in samples from different locations of the Main Fault and usually not more than a few microns thick. Considering the very low tensile strength of OPA in a direction perpendicular to the bedding-parallel foliation (Bock, 2001), it is not surprising that the cores fracture so easily along these zones.

We interpret the zones underneath the slickensides as thin shear zones, along which strongly localized deformation produced the observed fabric. With progressive deformation the shear zones can accommodate limited displacement because of their curvature before new shear zones nucleate (cf. Fig. 2 of Ingram et al., 1997). In the samples with widely-spaced shear zones, the surrounding OPA is only weakly deformed, as shown by the cusps in the fossils interpreted to
represent minor pressure solution (den Brok and Morel, 2001). In some other cases, lenses enclosed between shear zones are deformed more homogeneously (van der Zee and Urai, 2005) to produce gouge. With progressive deformation, the density of shear zones increases, forming an anastomosing network of scaly clay. Our first results show that this network occurs, interestingly, without much deformation inside the lenses. A perhaps surprising result of our observations is the absence of tips for the slickensides, which indicates that they propagated long distances for very small bulk deformations, terminating at branch lines in the shear zone network.

4.1 Thin shear zones

Although we did not find indicators of absolute displacement on individual slickensides and direct indicators of shearing like grains bending into the shear zone are rare, we interpret the shear zones to have displacements in the mm- to cm range (e.g. inferred from the tool track in Figure 3B). The data seem to indicate a relation between the slickenside - bedding angle and step length. We hypothesize that a relationship between slickenside morphology and displacements also exists, with surfaces like number (2) in Figure 3 representing small displacements, before the individual segments coalesce into a fully mobilized shear zone.

The internal microstructure of the thin shear zones (< 4 µm width) is characterized by (i) very strong preferred particle orientation, (ii) extremely low porosity, (iii) bending around larger grains, (iv) possibly more illite than in undeformed OPA (based on one FIB-TEM sample), (v) the presence of nanoparticles, and (vi) almost no transition zone from the undeformed fabric to the shear zone.

Tool tracks, such as the grain trace in Figure 3B, indicate frictional sliding in the shear zones (Hancock and Barka, 1987). Although we do not know the shear strength of these shear zones under conditions of natural deformation, the residual shear friction angle of Opalinus Clay, which
has been measured to be about 22º (Bock, 2001), is a safe upper bound for this. Therefore, these shear zones, once formed, are expected to localize deformation and to propagate rapidly (Collettini et al., 2009).

The shear zones anastomose around larger minerals and do not develop enough stress to fracture these grains (Jessell et al., 2009), contributing to the waviness of the shear zone. Thus, in surface view the continuously connected, smooth clay film is seen (Figure 4).

Frictional sliding and associated abrasive wear are common mechanisms for the generation of gouge and the mirror-like polishing of slickensides in brittle environments (Blenkinsop, 2000; Fondriest et al., 2013; Hancock and Barka, 1987; Tjia, 1964; Twiss and Moores, 1992). In claystones, this process can produce soft clay gouge even from strongly cemented shales (Holland et al., 2006). These mechanisms are commonly associated with inter- and trans-granular microcracking (Niemeijer et al., 2010). However, trans-granular microcracks are almost completely absent in our shear zones, in agreement with results from other clay gouges (Haines et al., 2013; Milliken and Reed, 2010).

This absence may indicate the importance of other mechanisms such as grain-boundary sliding, crystal plasticity of phyllosilicates, solution-precipitation processes or neoformation of clay minerals, associated with microscopically ductile creep. Slip on the (001) basal planes of clay particles is much easier than shearing related to grain breakage (cf. Haines et al., 2013). The abundant nanoparticles in the shear zone could have been formed by both, cataclasis and solution-precipitation processes, by recrystallization of kinked and folded clay mineral grains (Urai et al., 1980) and by neoformation of illite (Vrolijk and van der Pluijm, 1999). Although the smectite-illite transformation has been shown to occur preferentially in fault gouge (Vrolijk and van der Pluijm, 1999), we do not have sufficient evidence for this process, as we only analyzed
one TEM sample so far. However, the densely stacked illite aggregates in the shear zone of Figure 11E suggest that smectite-illite transformation could have occurred but this hypothesis should be further tested by analysis of the minerals in the micro shear zone and in the protolith (cf. Buatier et al., 2012b; Sasseville et al., 2012).

The actual processes of localization of strain during propagation of the shear zones and their relative importance could be studied at the tip of a propagating shear zone. Unfortunately, these features were not found so far. The reorientation of clay grains, fluid expulsion during pore collapse, formation of preferred particle orientation and strong grain-size reduction by cataclasis could all have been dominant mechanisms in the deformation of OPA. Testing this hypothesis requires further detailed analysis of mineralogy, microchemistry and isotope compositions.

4.2 Gouge

The microstructure of gouge is very different from that of the thin shear zones, defining the boundaries of the gouge. The gouges’ strong foliation defined by clay minerals anastomosing around larger, rounded, elongated grains of quartz and calcite, the very low porosity, the absence of large calcite grains all agree with strong, ductile deformation of the protolith, dissolution of grains and pore collapse being important micro-scale processes (cf. Bos, 2002; Niemeijer and Spiers, 2007, 2005; Niemeijer et al., 2008). This interpretation is also in agreement with the roughly similar composition of protolith and gouge matrix around larger grains measured by SEM-EDX. Evidence for cracking of grains and clay filling in the fractures is present but rare (Figure 14F).

The 1 - 2 µm thin shear zones, containing nm-sized clay minerals are present at the gouge zone boundaries (Y-shears sensu Logan et al., 1979). We suggest that the gouge forms by deformation of lenses between thin shear zones, driven by the stress increase in the lenses during deformation.
of the weak micro-shear zones (van der Zee and Urai, 2005). This interpretation is in agreement with the sigmoidal foliation in the gouge lenses.

Still, the micromechanisms driving the gouge evolution are difficult to identify. The removal of calcite inside the gouge and the high fabric intensity indicates pressure-solution in the lenses between thin shear zones. We hypothesise that particle comminution was a relevant micromechanism. However, even though individual grains at the host rock boundaries seem truncated by the thin shear zone (quarz grain on the left in Figure 14D), we cannot identify their missing counterparts neither inside the gouge nor in the host rock at the other side of the gouge.

The fact that trans-granular microcracks inside the gouge are rarely observed, might be explained by a gouge internal plastic deformation to maintain the P-orientation under ongoing deformation (cf. Haines et al, 2013). This process could lead to homogenization of the gouge microstructure, making it difficult to relate broken grain parts. The strong P-orientation of grains in gouge (S-C fabric, Figure 13 and Figure 14) has been described in nature and experiments (e.g. Sibson, 1977; Yan, 2001; Zulauf et al., 1990; Logan et al., 1979; Rutter et al., 1986; Haines et al., 2013). The total offset of the gouge bands might lay in the range of several cm to dm, with the thin shear zones at the gouge boundaries likely accommodating the majority of this offset, acting as Y-shears (cf. Logan and Rauenzahn, 1987). The absence of intra-granular microfractures and the strong particle alignment within the thin shear zones indicates stable sliding. This proposed process is in agreement with the interpretation of Y-shears as planes of stable sliding (Logan and Rauenzahn, 1987), which form subsequent to work hardening (e.g. accompanied by stress increase in lenses as stated above) and fabric change that, in our case, could be attributed to an initial comminution process. We cannot judge whether this feature represents a geological marker for seismic slip, as stated by Fondriest et al. (2013) for shears in dolostone gouge, or for sub-
critical (but repeated) crack-grow. The latter would match with a contemporaneous pressure solution process of Ca (section above). Moreover, a mechanical comminution could result in a decreased dissolution contact area, which, in turn, enhances the pressure solution process of Ca described above (cf. Gratier et al., 2014).

4.3 Veins

Veins are thin, locally fibrous and laminated (Figure 15E and F), which is a texture proposed to indicate crack-seal processes during shearing (Koehn and Passchier, 2000), with growth of calcite into dilation sites. Dilatancy is consistent with a slight overconsolidation of OPA (Cuss et al., 2011; Ingram and Urai, 1999) during the evolution of the Main Fault (Nussbaum et al., 2011).

Klinkenberg et al. (2009) reported the occurrence of inter-particle cracks connecting larger grains in the surrounding of shear zones in synthetically deformed OPA. Based on unconfined uniaxial compression tests on OPA, Amann et al. (2011) proposed the formation of microcracks around larger heterogeneities as a reason for failure far before rupture stress.

Crack-seal vein textures are commonly interpreted to indicate incremental opening of the crack, with crack apertures in the micron range. Calcite and celestite veins, clearly visible in thin section (Figure 15A and B), are interpreted to cause the brightness variances on the slickensides (Figure 3A). Laterally, they pass into the shear zone without veins, suggesting a distribution of veins as patches in the shear zone. The local, occasional presence of euhehedral, faceted grains indicates growth into free fluid and the presence of local open cracks.

Because of the slight curvature of the shear zones, shearing induces stress changes between releasing and restraining sections (Bürgmann and Pollard, 1992; Chester and Chester, 2000; van der Zee and Urai, 2005). In the slightly overconsolidated OPA, this curvature can be expected to lead to dilatancy and drop in fluid pressure in releasing sections and simultaneous precipitation of
calcite. This process indicates a mixed-mode failure generating hybrid extensional-shear fractures (sensu Sibson, 2000). The calcite was perhaps generated by dissolution in the gouge and migration through local cracks in the otherwise non-porous thin shear zones bordering the gouge lenses or came from an external source. Veins may locally restore the strength of some shear zones (Wintsch, 1998), but also provide regions of stress localization and propagation of shear. On the other hand, veins may also reflect higher fluid pressures indicating dilatant fracturing.

In our interpretation, the veins formed in evolving shear zones, contemporaneous with the reverse shearing, but after an initial nucleation of the shear zones. This interpretation is supported by the laminated microstructure (Figure 15) coherent with reverse shearing of the shear zones. The zones of grain-scale calcite enrichment (Figure 15C), also interpreted to have formed in releasing sections and associated with veins, are less easily explained. Our preferred explanation is that these are small relay zones, which failed in extension during early linkage of segments of the forming shear zones by distributed microcracking and simultaneous precipitation of calcite in the microcracks. In agreement with this, Vroliik and Sheppard (1991, Figure 11) show isolated fibrous carbonate spheroids, possibly indicating incipient filling of a fracture. Another explanation is that these zones of grain-scale calcite enrichment are tectonically disrupted veins (cf. Vrolijk and Sheppard, 1991). Figure 15E and F show a somewhat disordered vein structure supporting a tectonic reassembling. Whether this explanation applies for calcite enrichments in a releasing section such as the riser in Figure 15C is unclear.

4.4 Scaly clay

Tectonically derived scaly clay (Cowan et al., 1984; Labaume et al., 1997; Lundberg and Moore, 1986; Maltman, 1998; Moore and Byrne, 1987; Vannucchi et al., 2003) in the Main Fault develops in C’-type shear bands, but also in meso-scale folds and microfolds (Nussbaum et al.,
As suggested by the first results of this study, scaly clay consists of small, fish-shaped flakes of undeformed or weakly deformed OPA bound by slickensides. With the increase in density of shear zones, an anastomosing network develops, leading to macroscopically ductile shearing. An interesting question here is the dissipation of excess pore pressure that is locally created by collapse of the porosity during shear zone propagation: with widely spaced shear zones this dissipation is much easier than in a volume bound by a network of non-porous shear zones that presumably form permeability barriers, perhaps providing a feedback mechanism to generate local high density of shear zones and scaly clay. This interpretation is supported by Arch et al. (1988), who demonstrated that (1) small differences in water content can produce a large difference in both; the peak and residual strengths and that (2) higher water content leads to increased complexity in shear zone geometry in clays.

4.5 Implications to present-day permeability and paleo-fluid flow of the Main Fault

Tectonically undisturbed Opalinus clay has a very low permeability ($2 \times 10^{-13}$ m/s, Bossart and Wermeille, 2003). One of the most important results of this study for fluid flow and self-sealing models (e.g. Bock et al., 2005) is that in-situ the Main Fault contains a network of shear zones, veins and gouge with a much lower porosity than the protolith. This outcome is consistent with the measurement of no permeability increase in the Main Fault (Nussbaum and Bossart, 2008), but predicts that the present-day permeability of the Main Fault is much lower than that of the protolith. However, this present-day permeability can also be easily increased by microcracking along the very weak shear zones, e.g. caused by excavation, tectonic forces, or fluid pressure.

On the other hand, the occurrence of veins in shear zones are indictors for paleofluid flow along releasing segments of the shear zones, which localized fluid flow and finally contributed to resealing the fault by precipitation of calcite and celestite. Based on isotope profiles (Sr, S, O, C),
de Haller et al. (2014) suggested that OPA acted as a seal for fluid flow during most of its history except during the movement of the Main Fault. This interpretation is in full agreement with our results.

4.6 Mechanical properties of the Main Fault during tectonic deformation

The inferred fluid-assisted pressure solution and neocrystallization processes during tectonic deformation of the Main Fault are unlikely to occur in rapid laboratory experiments, but can be simulated by analogue experiments (Bos and Spiers, 2001; cf. Niemeijer et al., 2008). This matter means that the Main Fault during tectonic deformation had a different constitutive behavior than measured in the laboratory, and extrapolation of laboratory-derived mechanical properties to predict long-term creep deformation could be incorrect. The extrapolation of laboratory-derived mechanical properties is a good upper bound and during long-term creep faults in OPA are predicted to be weaker and more viscous.
5 Conclusions

- Thin, localized shear zones (< 4 µm width) are the elementary building blocks of the Main Fault, as they form an interconnected network through otherwise undeformed host rock. The shear zones comprise aligned and enveloped particles as well as nano-sized illites and have a dramatically reduced porosity compared to the protolith.

- Samples fracture preferentially along these shear zones, revealing highly polished slickensided surfaces. These fractures were however not open in the samples before coring.

- Tectonically derived scaly clay comprises fish-shaped flakes of undeformed OPA of less than 300 µm thickness bound by thin shear zones. Scaly clay developed by progressive increase of the density of thin shear zones.

- Calcite and celestite veins occur along some shear zones. Textures of the veins indicate crack-seal growth and only locally growth into a free fluid. Calcite enrichments are often associated to risers of the slickensides.

- Elongated and lenses of gouge (< 1 cm thick) are also found in the Main Fault, bound between thin shear zones. Gouge is strongly but more homogeneously deformed, with grain size and porosity reduction, removal of calcite grains by pressure solution and development of a tectonic foliation. We interpret the gouge to have formed in restraining bends between shear zones, and the veins in releasing bends.

- Microstructural evidence for cataclasis is rare.
6 Acknowledgements

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7 References


Haines, S.H., van der Pluijm, B. a., 2012. Patterns of mineral transformations in clay gouge, with examples from low-angle normal fault rocks in the western USA. J. Struct. Geol. 43, 2–32. doi:10.1016/j.jsg.2012.05.004


8 Figure Captions

Figure 1: Geology of the Mont Terri URL. A) Facies map, borehole locations indicated. B) 2D balanced cross-section after Freivogel and Huggenberger (2003).

Figure 2: A) Paleostress analysis from striae (Nussbaum et al., 2011). B) Small-scale map of the Main Fault in gallery 08 (see Figure 1 for location) modified after Nussbaum et al. (2011). C) Illustration of sample types and methods applied. OM = optical microscopy, SEM = scanning electron microscopy, BIB = broad ion beam milling, FIB = focused ion beam milling, TEM = transmission electron microscopy.

Figure 3: Compilation of slickenside photographs from well BIC-A1. Sided light was used to minimize reflections. Sketches illustrate the surface orientation towards bedding foliation (S0). Bold arrows indicate inferred movement of missing blocks. A) Sample BIC-A1-BL05 showing an intersection (branch line) of a wide stepped (1) and a narrow stepped (2) slickenside. Arrows (a) and (b) point towards darker and brighter areas on the slickenside, respectively. B) Detail of sample BIC-A1-BL03, showing a tool track of ca. 1.6 cm, which gives an estimate for the minimal offset along this slickenside. C) Detail of sample BIC-A1-BL03 illustrating polished vs. ragged parts. D) Slickenside from sample BIC-A1-BL06 with large step length, but oblique to bedding.

Figure 4: Sketch illustrating (left) the BIB setup and (right) the slickenside nomenclature used.

Figure 5: SEM images of a more narrow stepped (above) and a wider stepped (below) slickenside, samples BIC-A1-T1 and BIC-A1-U7, respectively. B) is an inset of A), in the lower left the FIB-TEM location is visible. C) is an inset of B). E) is an inset of D) (small arrow pointing to location) showing a bright (heavy) mineral underlining a thin clay film in BSE mode, 20 kV. F) is an inset of E). All images (except E) are SE2 images; A)-C) 5 kV, D) 20 kV, F) 8 kV. Bold arrows indicate inferred movement of missing blocks. Note the clay particles with sizes < 200 nm at highest magnification.

Figure 6: SEM images of sample BIC-A1-U5 in surface view (left) and side view (right). B) and C) are insets of A). Small arrows point to bright (celestite) lineations. Bold arrows indicate movement of missing block. B) shows facetted celestite (Ce) next to clay minerals (Cl). C) shows nano-sized particles in high magnification (SE2, 5kV). D) side view BSE image and E) sketch, showing laminated calcite (Ca) and celestite (Ce) veins next to the slickenside. F) inset of D) picturing a BIB polished section. G) inset of F) showing clay minerals (Cl) in between to laminated veins. See text for details. All images (except C) are BSE images, 20 kV.

Figure 7: A) Ultra-thin section image (xpol, gypsum plate) of sample BIC-A1-UTh6. B), C) and D) are insets of A) picturing gouge, a vein and a thin band next to the fracture. E) is a BSE micrograph (20 kV) of the sample location shown in D). F) is an inset of E) showing the bands thickness of approximately 4 µm. Qz = quartz, Ca = calcite, K-Fsp = kalium feldspar, Sid = siderite.

Figure 8: Slickenside of broken sample BIC-A1-U10 in side view (SE2 image, 5 kV). Note the nano-sized width of the thin band next to the slickenside bordering OPA with clearly undeformed bedding foliation (S0). C is an inset of B (white rectangle).

Figure 9: A) BSE micrograph (20 kV) of a resin (R) filled fracture in BIB-milled sample BIC-A1-S9. White arrows indicate nesting of a large pyrite grain (Py) into the opposite fracture wall. B) inset of A) showing the alignment of clay particles next to the fracture and how they envelop the larger pyrite grain. Note the pores of visible in the SE micrographs C) and D). E) and F) show the segmented pores (black) and the cell-wise porosity distribution (colour intensity) for the same locations than A) and B). Qz = quartz, Py = pyrite. Note that there is no visible trend in porosity towards the fracture wall, except from a thin zone (< 3 µm) of almost no visible porosity next to the fracture. See text for details.

Figure 10: BSE image (20 kV) of an open fracture separating a thin zone of aligned particles (sample BIC-A1-U2). B) is an inset of A). Arrow points to a tabular grain (probably mica) bent into the thin zone of aligned clay minerals. Note that porosity is almost absent in the thin zone. Qz = quartz, Ca = calcite, M = mica.
Figure 11: A) STEM (HAADF) mosaic of FIB lamella TEM1. B) is an inset of A), showing face-to-face aligned clay particles. C) is a sketch of B). D) is an inset of A), showing bent illite particles enveloping quartz grains. E) sketch of D). I = illite, M = mica, Qz = quartz, see text for details.

Figure 12: Detail STEM (HAADF) image of D, showing nano-sized illite particles, some examples marked by arrows.

Figure 13: Transmitted light microscope images of ultra-thin sections BIC-A1-UTh3 (A) and BIC-A1-UThB4 (B) (xpol, gypsum plate), showing lenses of gouge with sigmoidal particle orientations and darker colour. Compared to surrounding protolith. Arrows give inferred sense of movement. See text for details.

Figure 14: A) is an optical micrograph of thin section BIC-A1-Th3 showing a gouge lense (dark brown). B) inset of A) showing a calcite fossil with a straight edge at the gouge – protolith boundary. C) shows gouge internal fabric. D) pictures the sharp gouge – protolith boundary (between bold arrows). E) shows a thin shear zone in the gouge. F) shows a cracked quartz grain in the gouge. C), D), E) and F) (all BSE images, 20 kV) derive from sample BIC-A1-U8. Comparable locations are indicated in A), with E) and F) close to C), see text for details.

Figure 15: A) and B) are optical micrographs of ultra-thin section BIC-A1-UTh6 (xpol, gypsum plate) showing sharp vein – fracture boundaries with veins on both fracture sides in A) and a vein just on one fracture side in B). Arrow is pointing to a vein tip terminating in the protolith. C) is a reflected light micrograph from sample BIC-A1-U7 (sided light) illustrating calcite enrichment at a riser. D) is an inset of C). E) shows laminated veins (Lam.), for location see Figure 7A. F) pictures a laminated vein at the gouge-protolith boundary, see Figure 13B for location. D), E) and F) are BSE images taken at 20 kV. Ca = calcite, Qz = quartz.

Figure 16: A) is a photograph (sided light) of water immersed hand specimen BPS12-03, showing a distinct boundary of bedding foliation to scaly clay fabric along a sharp shear zone (dashed line in sketch B). C) and D) are photo and sketch of an inset in A).

Figure 17: A) is a reflected light microscope image of scaly clay flakes showing slickensides. B) is a high magnification SE (5 kV) micrograph showing nano-sized particles on a slickenside from a scaly clay flake (sample BPS12-3b). C) BSE micrograph of BIB-milled scaly clay flake suspended in resin. D) detail of C) showing a thin, non-porous zone of aligned particles at the flakes boundary.

Figure 18: Schematic model of faulted OPA from the Main Fault in the MT URL. Bold arrows indicate movement of the missing block.
A paleostress analysis from striae

C methods

(1) sample type

(2) slickensides

(i) breaking + OM + SEM
(ii) immersion in water + OM + SEM
(iii) ultra-thin sectioning + OM + SEM
(iv) BIB + SEM
(v) FIB + TEM

B bedding trace
gash plane with shear sense
tectonic breccia
correlation cleavage
EDZ extensional fracture (mode I)
arrow = azimuth/dip of fault plane
scaly clay
Highlights

1. We examine shear zones in slightly over consolidated Opalinus Clay.
2. We describe slickensides, thin shear zones (< 4 µm), gouge, veins, scaly clay.
3. Shear zones are dramatically reduced in porosity compared to the protolith.
4. Tectonically derived scaly clay shows no internal deformation of the microlithons.