

Responses to comments by reviewer #1

Zeynal Abiddin Erguler (Referee)

Received and published: 06 February 2021

Ref: se-2021-4-RC1

Dear Authors,

Please be informed that I read carefully your manuscript. I would like to say that the content and outputs of your research are very important for scientists investigating fracture closure and self-sealing of mudrocks. I have only below given minor comments on your manuscripts:

Response: We sincerely thank Zeynal Abiddin Erguler for his constructive comments and valuable suggestions, which greatly helped to improve the manuscript's quality. In the following, we provide a point-by-point response to the comments, where comments are in black, and our responses are in blue. In addition, any changes regarding "author responses to reviewer #1" applied in the revised manuscript are also marked in blue.

(1) Lines 16 and 403: The needle penetrometer cannot be used for geophysical characterization of rock materials. Only mechanical properties can be predicted by this index test. I suggest authors do not trust too much on predicted geophysical values and so the related empirical approaches of previous studies. Actually, you do not need these predicted parameters for this manuscript. Please apply proper modification.

Response: We agree. However, Aydan et al. (2014) demonstrated that ultrasonic P- and S-wave velocities can be roughly estimated by the NPI ($R^2 = 0.76$ and $R^2 = 0.76$, respectively), which was derived empirically from various tested lithologies.

Hence, we also applied the published empirical relationships in our study, compared and discussed the results in context to other studies in the literature. Finally, we were able to derive the following conclusion (page 23, line 467 in the marked manuscript):

"[...] it can be assumed that the relationship of ultrasonic velocity and NPI is probably rather weak."

This statement actually supports the reviewer's comment. Hence, we would like to keep this information in our manuscript as we also intend to demonstrate the limitations of needle penetrometer testing (NPT), which is at least valid for the studied claystone.

(2) The introduction part is very long and so it is very hard to see the main motivations of this study. This part should be shortened. Since there are many previous studies on physical and hydro-mechanical properties of Opalinus Clay, the contribution of this study should be more strong to convince readers to read the entire paper.

Response: We also agree. The introduction was therefore shortened in the marked manuscript. In order to emphasize the novelty and contribution as well as the scientific significance of the study more clearly, the last section of the introduction was adapted as follows (see also responses to the Topical editor recommendations):

"Hence, the objective of this study was to investigate the hydro-mechanical properties of the EDZ in the Opalinus Clay of the Mont Terri URL from in situ measurements on the exposed rock surface. We carried out a nondestructive and holistic determination of hydraulic and mechanical parameters of the fractured rock mass around a small tunnel niche, by combining transient-flow air permeametry, photomicroscopy and needle penetration tests. We characterized bulk rock properties of the

claystone, and quantified mechanical and hydraulic apertures of different fracture types of the EDZ, since these discontinuities can significantly control the overall material and flow behavior. We have also explored the alteration of the non-lined niche that was directly exposed to air for several years. By using the water content of the claystone, we compared the determined physico-mechanical parameters with data from other studies to assess the effect of desaturation directly on-site at the tunnel wall."

(3) Some of relationships given in Figure 6 (Fig 6c, d, f, g, h, and i) are not statistically significant. I recommend removing them.

Response: We partially agree. For some of the parameters shown in Figure 6, the deviation of the NPI derived values from the existing literature data sets is very large. Particularly for the determination of the Brazilian tensile strength and the Young's Modulus parallel to bedding, the needle penetrometer test results in a significant underestimation of the respective values, which was explained by the presence of bedding-parallel microcracks.

However, this information is essential for the application of this method to the investigated host rock (and possibly also for other anisotropic claystone formations in future investigations). Thus, the mentioned relationships between the NPT data and the literature data in Fig. 6 (subfigures c, d, f, g, h and i) should also be retained from our point of view. In the last part of Section 3.2, however, it is clearly stated that for the Opalinus Clay the method is mainly suitable for determining the uniaxial compressive strength and that bedding-parallel measurements can lead to a poor estimation (page 23, lines 477-478 in the marked manuscript).

(4) The manuscript looks very long. It would be a little difficult to read without getting bored for those who do not work on this subject. Please shorten your manuscript by removing unnecessary evaluations, discussion and outputs of previous studies.

Response: We agree. Apart from the introduction according to comment (2) above, also some discussion parts of Section 3 were shortened (page 14, lines 261-276 and page 15, lines 297-304 in the marked manuscript).

Except for the discussion on predicted P-wave and S-wave velocities, the content of this manuscript looks interesting. So I recommend minor revision for this submission.

Regards

Zeynal

Responses to comments by reviewer #2

Anonymus Referee #2 (Referee)

Received and published: 11 March 2021

Ref: se-2012-4-RC2

General comments

Research question

The current research paper addresses the question of how to easily, cost-effectively and non-destructively investigate the (time-dependent) evolution of a discrete fracture network (DFN) in an excavation damaged zone (EDZ) of an unlined lateral adit to draw conclusions for storage safety of e.g. long-term nuclear storage waste disposal. The usefulness of the proposed set of partially in-situ methods is shown by a comparison of the authors own results based on an acquired dataset in a small, unlined niche of the Mont Terri URL in Switzerland with the vast data repository from numerous scientific investigations conducted in the same overall location since 1996 (=25 years). The authors present a four-fold dataset (measured in April 2019) consisting of:

- (43) direct measurements of hydraulic fracture aperture a_h using an air permeameter on rough fracture surfaces;
- (36) estimations of both mechanical fracture aperture a_m coupled with fracture surface roughness δ_m by the use of image analysis on a set of microscopic images on rough fracture surfaces (methodology and an automation thereof recently published by the main author);
- (47) direct measurements of needle penetration indices (NPI) perpendicular and parallel to bedding on rough fracture surfaces;
- (2) indirect measurements of the water content of an opalinus clay sample.

The set of estimated mechanical aperture a_m values and the fracture surface roughness δ_m values derived from image analysis are then related to equivalent hydraulic fracture apertures $a_{h,eq}$ via a cubic law additionally requiring single fracture transmissivities T_f measured at Mont Terri URL in other studies for plausibility purposes. The set of of NPI measurements are subsequently split into two categories (parallel and perpendicular to bedding) and a range of geomechanical and geophysical parameters calculated on a range of empirical relationships readily available in literature. Together with the determined water content of a representative sample the calculated parameters are then related to the ones available by other studies from Mont Terri data repository.

Through a classification of the investigated fractures as artificially induced unloading fractures (called "EDZ fractures"), reactivated fault planes/splays (called "tectonic fractures") and bedding-parallel desiccation/unloading cracks the directly measured and derived data is then set into context of the temporal development of the EDZ in the investigated niche and to the whole Mont Terri URL project.

Response: We sincerely thank the anonymous Referee #2 for his or her detailed and constructive comments, which helped to substantially improve the manuscript. In the following, we provide a point-by-point response to the comments, where comments are in black, and our responses are in blue. In addition, any changes regarding "author responses to reviewer #2" are highlighted blue in the marked revised manuscript.

Contribution of work

(1) Presentation quality: The presentation quality of the paper is considered Excellent (1) as it is very well structured, nicely illustrated (plots and figures) and clear by not mixing its own observations with already existing and new interpretations. The abstract is of very good quality. The use of the English language is concise, does not suffer from any noticeable flaws and therefore overall makes a joyful read.

(2) Scientific quality: The scientific quality of the current paper is assessed as Good (2) as it uses well-established approaches (i.e. air permeameter) and available data from the site as well as the vast knowledge of the Mont Terri URL site to accurately assess the performance and limitations of the authors own microimage-methodology and its applicability to similar investigations.

(3) Overall scientific significance: The question to find an easy-to-apply methodology to characterize the time-dependent evolution of a DFN in an EDZ is interesting as well as important. The investigation of the bulk material (i.e. different facies of opalinus clay) and derived bulk chemical and physical properties as well as effective medium approximations only show the side of the story where material behavior is controlled by the bulk medium only. Although the bulk material properties may be very favorable, very local discontinuities created during excavation ("EDZ fractures") and first and foremost local to regional (re-activated) tectonic discontinuities and the transport properties along them very likely play – apart from the above mentioned bulk material considerations - a very important role in the assessment of storage safety in the host rock.

Response: We appreciate the positive assessment of the quality of the submitted manuscript and of the overall scientific significance of the research question.

(4) Scientific significance of the paper: The main contribution of this research lies in the comparison of the acquired dataset of hydraulic fracture apertures a_h determined by an commercial-of-the-shelf air permeameter with the mechanical fracture aperture a_m coupled with fracture surface roughness δa_m determined by the image analysis approach of the first author (i.e. Hale et al., 2020b). As the conversion of geometrically measured parameters ($a_m, \delta a_m$) to hydraulic fracture apertures a_h relies on empirical relationships, plausibility of the converted values – as mentioned by the authors – rely on fracture transmissivities T_f measured by other methods (e.g. borehole geophysics) in the same overall location. Therefore, the current study as a use case for the first authors own microimage-methodology accurately depicts its main advantages (i.e. measurement range, spatial resolution) but also its own main limitation mainly due to reliance on empirical relationships as well as due to the related error propagation of large standard deviations due to variable fracture surface roughness. If looked at from the angle of a use case of an already published methodology paper, the current research paper deserves its merit – coupled with independently acquired direct measurements of a_h or via T_f – as an incremental advance in the field of non-destructive, cost-effective, in-situ determination of hydraulic fracture parameters. The microimage-method is – as indirectly pointed out by the authors – however not a standalone method for the determination of hydraulic fracture parameters (=geometric method) that can be used independently of direct physical methods (=kinematic methods).

If the research paper is however considered as its wrapping suggests (i.e. the advancement of the understanding of EDZ in opalinus clay for long-term nuclear storage), it falls short of its aim of significantly extending the knowledge by its new dataset provided compared to the one that is already available from the investigated site and conclusion already drawn in previous studies (i.e. knowledge of seasonal cycles, inhibition of long-term convergence, significance of discontinuity types, dependency of strength on water content, problems with low humidity environment, shotcrete application to counter dehydration etc.). The determination of NPI as an

extension of the papers dataset does – in the eye of the reviewer – by itself not extend the scientific knowledge of the strength anisotropy of (altered) layered geologic media (e.g. opalinus clay) as similar methods (e.g. Schmidt hammer) have readily been used by engineering geologists and geotechnical engineers for decades. The scientific significance of the paper is therefore assessed as Good (2) if considered as a use case for Hale et al. (2020b) but overall as Fair (3) in its current form and wrapping and in the scope of the journal Solid Earth (SE).

Response: We partially disagree. Since comment (5) also partly questions the scientific significance of the manuscript, we would like to refer to our response to comment (5), where we explained the contribution and relevance of the presented study in more detail.

(5) Summary: Although the manuscript is very well built and structured as well as very nicely and clearly presented, it unfortunately falls short by not producing an overall dataset that adds to the already vast data repository of Mont Terri URL and does by itself not offer new interpretations and conclusions that significantly add to the understanding the temporal evolution of EDZ in opalinus clay. At the bottom line, it is therefore questionable in the eye of the reviewer if the current manuscript represents a substantial contribution to scientific progress in the scope of Solid Earth but would rather be suited to a more specific journal.

Response: First and foremost, the applied combination of three different non-destructive measurement methods is absolutely novel.

The presented methodical-analytical approach was successfully used for a holistic hydro-mechanical characterization of an EDZ in a potential host rock formation for nuclear waste disposal. Thus, the presented approach is certainly of great importance for future investigations, since required parameters of the bulk rock and the fracture network can be determined accurately using only simple measuring methods.

Due to the fact that the new combined approach was compared with pre-existing data, the measured values yielded conclusions that are already known from previous studies (significant anisotropy of the Opalinus Clay, dependence of strength and stiffness on the water content, influence of the saturation state on fracture permeability or aperture in the EDZ). In addition, however, other important results and new interpretations emerged from this study that are relevant both for the characterization of host rocks for nuclear waste disposal and for the characterization of EDZs in tunnels:

- The Opalinus Clay in the vicinity of a tunnel (on site) actually behaves as assumed on the basis of the extensive laboratory tests on smaller core samples.
- Determination of mechanical and hydraulic fracture apertures with an advanced form of the microimaging method developed by the first author. In contrast to the publication of Hale et al. (2020) mentioned by the reviewer, the method was automated to enable characterization of a higher number of fractures within short time. In addition, the submitted manuscript shows that microimaging of fracture traces also enables further geometric considerations on formation mechanisms.
- Regardless of the lithology (e.g. sandstone (Hale et al., 2020), claystone (this study)), it is shown that the equation from Kling et al. (2017) is most suitable for the estimation of the hydraulic aperture (a_h) based on fracture trace imaging and can therefore be highly recommended for future use. It is also shown that the median is the most suitable parameter to provide a representative measure of the mechanical aperture of a fracture network.
- Air permeameters are primarily used for determining the matrix permeability of rocks. We extend the application range of the measurement method to a discrete fracture network (DFN) of an EDZ within the scope of nuclear waste disposal.

- When applying the needle penetrometer test (NPT) to determine geomechanical properties in bedding-parallel direction, the respective parameters can be significantly underestimated. This finding was explained by the presence of bedding-parallel microcracks and may therefore also apply to other anisotropic claystone formations.
- The study yields therefore several new data sets:
 - Various geomechanical parameters of the Opalinus Clay (shaly facies) for various water contents obtained by a measurement method not previously used for this lithology. It should also be mentioned that these data reflect a ‘naturally’ adjusted saturation state without artificial drying or saturation (several years of exposure).
 - Mechanical and hydraulic fracture apertures (a_h , a_m) of different EDZ fracture types in the Opalinus Clay. To our knowledge, there is no such data set available yet.
 - Extensive compilation of existing physico-mechanical literature data. To our knowledge, such a compilation in its presented form has not been published yet. This data compilation could be used for modeling that also includes, for example, sensitivity analyses, as the range of values for different important parameters can be identified and quantified.

The submission of the manuscript to the journal Solid Earth with its interdisciplinary scope is supported by the fact that the presented methods and results can also be applied and transferred to different research topics and questions addressed by the journal.

In order to emphasize the contribution of the study as well as the scientific significance of the manuscript more clearly, the last section of the introduction was adapted (page 4, lines 117-128 in the marked manuscript, see also response to comment (2) of Reviewer #1 and the responses to the Topical editor recommendations).

Specific comments – Questions/Issues

(6) Positive:

- Setting the scene for the significance of the overall research question in the introduction by comparing bulk rock considerations vs. different behavior of EDZs;
- Relating the later measured hydraulic fracture apertures to the main hydraulic fracture parameters;
- Establishing the chosen methods "permeameter" + "microimaging" as easy to carry out in-situ alternatives to lab methods of borehole geophysics;
- Good characterization of the study site (2.1) with detailed references;
- Suitability of air permeameter measurements for the current study with its compatibility for advective flow;
- Comprehensive and well-written description of image analysis method (Section 2.3);
- Table 1 und Table 2 for the relevant conversion of measured parameters to calculated parameters later on;
- Structural maps of the niche with data plot and KDE – very nicely illustrated!
- Figure 5: very nicely illustrated key plot of the study;
- Line 370: Clear and honest statement that direct measurement of a_h is preferable (variety of empiric relationships; error propagation etc) but microimaging offers additional geometric considerations that the hydraulic aperture does not;
- Conclusion: Fracture traces indeed offer a complementary (but not alternative) method to indirectly look at hydraulic fracture apertures;
- The "methodological trinity" indeed offers an interesting low-cost but somewhat limited approach to look at the temporal evolution of fractures in an EDZ.

Response: We are pleased that so many points stood out positively while reviewing our manuscript.

(7) Shortcomings:

- Although the methodological "trinity" (i.e. air permeameter, microimaging, NPI-testing) is praised for its suitability of time-dependent monitoring of EDZ, it is however in the current study only applied at one point in time and then somehow related to the initial state after excavation. Therefore no temporal evolution is shown but only inferred by comparison to other studies;

Response: The aim of the study was to characterize an EDZ in a simple but effective way with regard to its hydro-mechanical properties. In the submitted manuscript, only in the Abstract (page 1, line 23) and in the Conclusion (page 25, line 520) it was pointed out that this combination of methods is in principle suitable for a time-dependent monitoring of an EDZ. Since the hydraulic properties of the discrete fracture network and the mechanical properties of the bulk rock can be determined non-destructively and, in particular, without introducing artificial changes to the system, the same section of an EDZ can be tested repeatedly over a longer period of time.

- Schmidt hammers have been used by geologists in the industry for much longer than indicated by the authors (Line 111; oldest reference from 2007);

Response: We agree that the Schmidt hammer and also the needle penetrometer test (NPT) has been used for a longer period of time than the cited references imply. We have therefore added the following references (page 4, line 112 in the marked manuscript):

Hucka, V.: A rapid method of determining the strength of rocks in situ, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 2, 127–134, [https://doi.org/10.1016/0148-9062\(65\)90009-4](https://doi.org/10.1016/0148-9062(65)90009-4), 1965.

Okada, S., Izumiya, Y., Iizuka, Y., and Horiuchi, S.: The estimation of soft rock strength around a tunnel by needle penetration test, J Jpn Soc Soil Mech Found Eng, 33, 35–38, 1985.

- Line 232: Were only nine (9) EDZ fractures measured? If yes, it is hard to make a significant statement based on a statistic comprising only nine values;

Response: The information given on page 11, line 232 in the submitted manuscript relates to all measurable fractures in the niche, which are affected by the EDZ of the EZ-B niche (reactivated and newly formed discontinuities). The information given in line 234 explicitly refers to the newly formed "EDZ fractures" (artificially induced unloading joints). Due to the subsequent application of shotcrete in the entrance area of the niche, less EDZ fractures were available for measurement compared to the tectonic fractures.

For clarity, we specified the respective number of measurements for each fracture type (pages 11-12, lines 240-246 in the marked manuscript).

- Line 366: Related to Line 232: if only nine (9) EDZ fractures were measured, what significance does the statement have?

Response: The observation was made using the available data and was therefore addressed in this context, although the number of measurements of the two fracture types was different. However, also with regard to the last comment, we pointed out the limited number of measured values here (page 18, lines 374-376 in the marked manuscript):

"While EDZ fractures seem to better correspond to the general model concept of an "ideal plane-parallel fracture", tectonic fractures are most probably characterized by a different a_m - a_h -relation.

While implied by the presented measurement data, this issue should still be examined based on larger data sets.”

- Line 388ff: The data does not exhibit new findings but rather underlines existing knowledge (i.e. strength dependency on water content and fabric);
- Figure 6: although very nicely illustrated again, the addition of only one (1) dot to the compiled plots does not really underline the significance within the range of the all the data available;
- Section 3.2 does not offer a directly measured new dataset but only a calculated set of data points that does not offer room for a new interpretation. All the mentioned findings have already been reported in the (always properly referenced) literature;

Response: We partially disagree with the last three comments. In Section 3.2 of the submitted manuscript we show that the needle penetrometer is suitable for the Opalinus Clay and provides reliable results, which was enabled by a comparison of the calculated values based on the needle penetration index (NPI) with compiled literature data sets. The agreement of the new data set with the existing data and knowledge clearly confirms that the needle penetrometer estimation expresses the anisotropy as well as the strength properties of the Opalinus Clay, although only a mm-sized area of the rock surface is tested by the device.

Section 3.2 actually includes a new data set based on a measurement and estimation procedure that differs from all existing literature data. One of the authors was also involved in the creation of the NPI dataset from 2013, but these results have not been compared to other data yet and are therefore revisited here. Overall, this results in a needle penetrometer data set for the shaly facies of the Opalinus Clay for nine different saturation states with water contents varying between 0 wt.% and 6.5 wt.%.

In addition, for some of the mechanical parameters considered, the compiled literature data set was also extended. In particular, for the uniaxial compressive strength (UCS) and the Young’s modulus (E), no measured values obtained by conventional methods were available for low water contents (< 5 wt.%) normal to bedding.

- Conclusion: There is not enough data to make comparative statement of EDZ fractures (n=9!) vs. Tectonic Fractures (n=31) that would underline a statistically significant trend.

Response: We agree, but we are convinced that the data and the conclusion is important for the reader and therefore we would like to keep this conclusion. In addition, the presented comparative examination including both geometric and hydraulic characteristics of different fracture types can provide a starting point for future studies.

Technical Corrections

- Line 34: Is EdZ used as a synonym for EDZ?

Response: EdZ is not used as a synonym for EDZ. The abbreviation EDZ denotes the excavation *damaged* zone, where significant changes in flow and transport properties are observed. EdZ designates the excavation *disturbed* zone, where the hydraulic properties of the rock are only scarcely affected. These abbreviations were already defined in the submitted manuscript (page 1, lines 27-28 and page 2, lines 30-35).

- Line 46: Please introduce the expression THMC for the general audience;

Response: The term THMC (thermal, hydrological, mechanical and chemical) was introduced accordingly (page 2, line 47 in the marked manuscript).

- Line 139: EDZ fractures – is that distance measured along the niche or radial to the niche?

Response: The specified distance refers to the depth along the niche, where EDZ fractures originating from the excavation of the adjacent Gallery 04 are present. For clarification, the respective sentence was modified (page 5, lines 144-145 in the marked manuscript, see also Responses to Topical Editor recommendations):

“Excavation-induced unloading joints (EDZ fractures) that are related to the construction of Gallery 04 are present within the first 1.3 m depth into the EZ-B niche (Nussbaum et al., 2005).”

- Line 178: Do you mean "arithmetic mean" or "geometric mean"?

Response: We were indeed referring to the arithmetic mean here, as already stated in the submitted manuscript.

Responses to Topical editor recommendations

Virginia Toy (Topical editor)

Received and published: 22 May 2021

Ref: se-2012-4-EC1

I have read over the referee comments, and your responses, and also checked the changes you made to the manuscript. I mostly think you've done a good job of addressing their concerns, and I find the manuscript to be scientifically sound and worthy of publication.

Response: We thank the Topical editor Virginia Toy for her recommendations, which are reasonable and helpful. In the following, we provide a point-by-point response to each comment, where comments are in black, and our responses are in red. In addition, the changes regarding "author responses to Topical editor recommendations" are highlighted in red in the marked revised manuscript, while the previous changes related to the reviewers' comments are highlighted in blue.

However, there are a couple of places where I recommend you do a little bit more work to adequately address the reviewer's comments and further improve the manuscript, as follows:

I would re-write your revised intro sentences as follows:

"Hence, the objective of this study was to investigate the hydro-mechanical properties of the EDZ in the Opalinus Clay of the Mont Terri URL from in situ measurements on the exposed rock surface. We carried out a nondestructive and holistic determination of hydraulic and mechanical parameters of the fractured rock mass around a small tunnel, by combining transient-flow air permeametry, photomicroscopy, and needle penetration tests. We characterised bulk rock properties of the claystone, and quantified mechanical and hydraulic apertures of different fracture types of the EDZ, since these discontinuities can significantly control the overall material behavior. We have also explored alteration of a non-lined niche that was directly exposed to air for several years *and then say WHY and HOW you did this.*

Response: We agree. Thank you for the suggested changes to the introductory sentences of the manuscript. We have mostly adopted the wording given above and have expanded it accordingly (page 4, lines 117-128 in the marked manuscript):

"Hence, the objective of this study was to investigate the hydro-mechanical properties of the EDZ in the Opalinus Clay of the Mont Terri URL from in situ measurements on the exposed rock surface. We carried out a nondestructive and holistic determination of hydraulic and mechanical parameters of the fractured rock mass around a small tunnel niche, by combining transient-flow air permeametry, photomicroscopy and needle penetration tests. We characterized bulk rock properties of the claystone, and quantified mechanical and hydraulic apertures of different fracture types of the EDZ, since these discontinuities can significantly control the overall material and flow behavior. We have also explored the alteration of the non-lined niche that was directly exposed to air for several years. By using the water content of the claystone, we compared the determined physico-mechanical parameters with data from other studies to assess the effect of desaturation directly on-site at the tunnel wall."

Reviewer 1 criticised inclusion of discussion of the P and S wave velocity. You did not respond to their comment. Please provide some sort of response.

Response: We already addressed this point in our response to comment (1) of reviewer #1. Here we have outlined that the empirical relations we used to estimate the P- and S-wave velocities are existing published equations, which led to satisfactory results in the study of Aydan et al. (2014) and can in principle also be used for the investigated claystone.

In agreement with reviewer #1, however, we also found that the estimation procedure based on the needle penetrometer tests is less suitable for determining P- and S-wave velocities in the Opalinus Clay than for the geomechanical rock parameters, which we discussed in the manuscript (page 23, lines 465-467 in the marked manuscript):

“As ultrasonic velocity is explicitly dependent on the internal structure of the rock, such as cementation, anisotropy and porosity structure (Jaeggi and Bossart, 2014; Schuster et al., 2017), it can be assumed that the relationship of ultrasonic velocity and NPI is probably rather weak.”

However, since these are published equations, we find it important to show and evaluate the results for the estimated geophysical parameters in addition to the geomechanical parameters.

Reviewer 2 criticises the statistical basis of the conclusions you reach about the EDZ fractures because your analyzed dataset is very small. You don't acknowledge this small dataset well enough in the current conclusions. Please add a statement about this.

Response: We agree that the analyzed EDZ fracture dataset is rather small due to the limited number of accessible measurement points in the niche, but we are fully convinced that the data and the conclusion is still important for the reader. However, we agree that this point should also be addressed in the conclusion and we have therefore revised the respective text passage and added a statement as requested (page 24, lines 513-514 in the marked manuscript):

“Due to the smaller mean mechanical aperture of the artificially induced unloading fractures compared to the investigated tectonic fractures, conversion was most appropriate for the EDZ fractures. Tectonic fractures on average exhibit a higher variance of measured distances along imaged fracture traces, which can be explained by a higher degree of mismatch between the fracture surfaces due to the reactivation of fault planes during excavation. However, the statistical significance of the observed differences between the different fracture types would have to be tested based on a larger dataset.”

In addition, we have already included a statement on the small size of the EDZ fracture data set in Section 3.1.3, as stated in our response to comments of reviewer #2 (page 18, lines 374-376 in the marked manuscript):

“While EDZ fractures seem to better correspond to the general model concept of an “ideal plane-parallel fracture”, tectonic fractures are most probably characterized by a different a_m - a_h -relation. While implied by the presented measurement data, this issue should still be examined based on larger data sets.”

THMC at line 47. The reviewer's point was that you never define the full term, just go straight to the acronym. You must give the full version here too.

Response: We agree and therefore inserted the full term in addition to the acronym at this point (page 2, line 47 in the marked manuscript):

“[...] and to examine the behavior of the Opalinus Clay when exposed to short- or long-term THMC (thermal, hydrological, mechanical and chemical) impacts (Bossart et al., 2017; Pearson et al., 2003).”

Line 142: I don't find your revision clear enough. Why not just clearly say 'within the first 1.3 m depth into the niche'?

Response: We agree and have changed the corresponding sentence in the manuscript as suggested (page 5, lines 144-145 in the marked manuscript):

“Excavation-induced unloading joints (EDZ fractures) that are related to the construction of Gallery 04 are present within the first 1.3 m depth into the EZ-B niche (Nussbaum et al., 2005).”

Mechanical and hydraulic properties of the excavation damaged zone (EDZ) in the Opalinus Clay of the Mont Terri Rock Laboratory, Switzerland

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Abstract. Construction of cavities in the subsurface is always accompanied by excavation damage. Especially in the context of deep geological nuclear waste disposal, the evolving excavation damaged zone (EDZ) in the near field of emplacement
10 tunnels is of utmost importance concerning safety aspects. As the EDZ differs from the intact host rock due to enhanced hydraulic transmissivity and altered geomechanical behavior, reasonable and location-dependent input data on hydraulic and mechanical properties is crucial. Thus in this study, a hydro-mechanical characterization of an EDZ in the Mont Terri underground rock laboratory, Switzerland, was performed using three different handheld devices: (1) air permeameter, (2) microscopic camera and (3) needle penetration test. The discrete fracture network (DFN), consisting of artificially induced
15 unloading joints and reactivated natural discontinuities, was investigated by a portable air permeameter as well as combined microscopic imaging with automatic evaluation. Geomechanical and geophysical characterization of the claystone was conducted based on needle penetrometer testing at the exposed rock surface. Within the EDZ, permeable fractures with a mean hydraulic aperture of $84 \pm 23 \mu\text{m}$ are present. Under open conditions, self-sealing of fractures is suppressed and cyclic long-term fracture aperture oscillations in combination with closure resulting from convergence processes, is observed. Based on
20 measured needle penetration indices, a uniaxial compressive strength of $30 \pm 13 \text{ MPa}$ (normal to bedding) and $18 \pm 8 \text{ MPa}$ (parallel to bedding) was determined. Enhanced strength and stiffness is directly related to near-surface desaturation of the claystone and a sharp decrease in water content from 6.6 wt.-% to 3.7 wt.-%. The presented methodological approach is particularly suitable for time-dependent monitoring of EDZs since measurements are nondestructive and do not change the actual state of the rock mass. This allows for a spatially resolved investigation of hydraulic and mechanical fracture apertures,
25 fracture surface roughness as well as physico-mechanical rock parameters and their intra-facies variability.

1 Introduction

For all types of man-made underground structures, formation of a so-called excavation damaged zone (EDZ) or excavation disturbed zone (EdZ) is inevitable (Pusch and Stanfors, 1992; Shen and Barton, 1997). As geologic formations are affected by regional or local stress fields, stress redistribution during excavation leads to displacement and convergence, accompanied by

30 the formation of unloading fractures in the rock mass around the cavity (Bossart et al., 2002). The EDZ is characterized by severe hydraulic, mechanical and geochemical modifications as well as newly formed connected porosity (Dao et al., 2015; Kupferschmied et al., 2015; Labiouse and Vietor, 2014; Sato et al., 2000; Yong et al., 2017). Thus, significant changes in flow and transport properties can be observed in the EDZ due to an enhanced permeability of the connected fracture network serving as preferential flow paths. In the EdZ, flow and transport properties are only scarcely affected ~~as potentially saturated fractures~~
35 ~~are mainly isolated and occurring processes are reversible~~ (Bossart et al., 2002, 2004; Tsang et al., 2005). The EDZ and its impact on hydraulic and mechanical rock properties are of particular importance for the underground storage of radioactive material (Blümling et al., 2007; Fairhurst, 2004). According to the current state of knowledge, multi-barrier systems for geological disposal are the preferred option for effectively isolating high-level nuclear waste and spent fuels (Birkholzer et al., 2012; Chapman and Hooper, 2012). ~~This repository concept is designed for a~~ A service life of up to one
40 million years, ~~which~~ will essentially be guaranteed by the sealing function of a natural barrier (Apted and Ahn, 2010; Wilson and Berryman, 2010). In Switzerland, the Opalinus Clay, an overconsolidated Jurassic claystone, was selected as a host rock for deep geological storage of high-level radioactive waste (Bossart et al., 2017; Nagra, 2002). In the context of host rock characterization and site assessment, the generic underground rock laboratory (URL) Mont Terri provides a valuable site for research, testing and development of in-depth technical know-how. Since 1996, numerous studies and experiments have been
45 conducted in order to evaluate ~~the hydrogeological, mechanical, geochemical and transport~~ essential properties of the undisturbed and altered rock, and to examine the behavior of the Opalinus Clay when exposed to short- or long-term THMC ~~(thermal, hydrological, mechanical and chemical)~~ impacts (Bossart et al., 2017; Pearson et al., 2003). Besides the Mont Terri URL in Switzerland, a number of underground laboratories in other countries and their potential or selected host rock formations are in operation, mainly in crystalline rocks (e.g. Äspö Hard Rock Laboratory in Sweden) ~~or sedimentary rocks~~
50 ~~including and~~ plastic ~~or indurated~~ clays (e.g. HADES URL in Belgium,) ~~and stiff or indurated clays (e.g. Meuse/Haute-Marne URL and Tournemire URL in France)~~ (Blechs Schmidt and Vomvoris, 2010; Delay et al., 2014). Similar to the Opalinus Clay in Switzerland, the EDZ and its impact on hydro-mechanical characteristics of the rock mass in the near field of underground structures is of particular interest for the Callovo-Oxfordian claystone in France (e.g. Armand et al., 2014; Baechler et al., 2011; Menaceur et al., 2016) as well as for the Boom Clay in Belgium (e.g. Bastiaens et al., 2007; Dao et al., 2015).
55 In the Opalinus Clay of the Mont Terri URL, the EDZ is characterized by a significantly enhanced hydraulic conductivity of 1×10^{-14} to 1×10^{-5} m s⁻¹ (Bossart et al., 2004; Jaeggi and Bossart, 2014; Marschall et al., 2017), whereas for undisturbed conditions it ranges between 2×10^{-14} to 5×10^{-12} m s⁻¹ (Jaeggi and Bossart, 2014; Lavanchy and Mettier, 2012). ~~In intact rock,~~ ~~substances are only transported by diffusive processes (Croisé et al., 2004).~~ Within the EDZ, advective transport is facilitated due to fracture permeability, which is several orders of magnitude higher than the matrix permeability of the claystone
60 (Marschall et al., 2017). Hydraulic fracture parameters such as permeability, transmissivity or flow rate are in turn directly related to the hydraulic fracture aperture a_h (Zimmerman and Bodvarsson, 1996), which therefore represents a key parameter for assessing the hydraulic characteristics of a fractured rock mass or an EDZ. The hydraulic aperture is usually derived from the cubic law (Louis, 1969; Snow, 1965) and relates to the mean opening width of a fracture accessible to advective transport.

Due to the confirmed self-sealing capacity of the Opalinus Clay caused by swelling of mixed-layer illite-smectite clay minerals (e.g. Bernier et al., 2007), the hydraulic conductivity of the EDZ is expected to decline within a period of several tens to hundreds of years by progressive fracture closure (Jaeggi and Bossart, 2014). In addition, fractured rock masses are also characterized by a pronounced hydro-mechanical coupling, i.e. changes in the mechanical stress state result in changes of permeability and therefore hydraulic fracture aperture (Cammarata et al., 2007; Min et al., 2004; Rutqvist and Stephansson, 2003). Generally, a_h is nonlinearly linked to the mechanical fracture aperture a_m in dependence of fracture surface roughness (Blum et al., 2009; Renshaw, 1995), for example via the Barton–Bandis model using the ~~well known~~ Joint Roughness Coefficient (JRC) (Barton, 1982; Barton et al., 1985). The mechanical fracture aperture represents the average geometrical distance between the fracture surfaces (e.g. Hakami and Larsson, 1996) and is needed to examine the response of fracture networks due to normal or shear stresses, ~~such as fracture dilation or closure mechanisms~~ (e.g. Blümling et al., 2007; Cuss et al., 2011; Zhang, 2016) or mechanical self-sealing of artificial fractures (e.g. Marschall et al., 2017; Nagra, 2002).

Similar to the hydraulic properties, mechanical properties of the Opalinus Clay diverge significantly depending on direction, facies and stress regime (Bock, 2009; Giger et al., 2015). Furthermore, ~~a strong dependency of failure strength and elastic parameters on water content or suction was proven (Jaeggi and Bossart, 2014; Wild et al., 2015)~~. Due to a ~~this marked and~~ clay-specific hydro-mechanical coupling (Amann et al., 2017; Marschall et al., 2017), geomechanical parameters such as uniaxial compressive strength, tensile strength and shear strength as well as the Young’s modulus of the Opalinus Clay generally increase with decreasing water content (Blümling et al., 2007; Wild et al., 2015). ~~In the EDZ in Mont Terri, elastic P and S wave velocity is significantly reduced due to the high degree of damage (Schuster et al., 2001, 2017)~~. Furthermore, geomechanical properties of the Opalinus Clay in the EDZ are also modified in comparison to the undisturbed rock mass. In the short-term, a reduction in effective stress caused by pore pressure excess in the vicinity of the advancing excavation front leads to early damage of the rock around the cavity. Right after excavation, pore water drainage, ~~pore pressure dissipation as~~ well as and increased suction of the rock mass can be observed close to the cavity (Amann et al., 2017; Giger et al., 2015). In the long-term, a general decrease in water content caused by dehydration of the rock leads to locally enhanced rock strength and stiffness (Wild et al., 2015).

An accurate and comprehensive hydraulic and mechanical characterization of the EDZ is therefore essential for confirming the integrity of the host rock in terms of risk and performance assessment (e.g. Blum et al., 2005; Popp et al., 2008; Tsang et al., 2015; Xue et al., 2018). This key information serves as an appropriate starting point for numerical modeling studies investigating the development of the EDZ in the post-closure phase of the repository, and is also useful for the selection and adaptation of engineering designs or adequate constructional measures (e.g. Hudson et al., 2005; Marschall et al., 2017; Nagra, 2019; Tsang et al., 2012). This does not only apply to the issue of nuclear waste disposal, but also generally to other underground structures in different geological materials and settings (e.g. Li et al., 2012; Sheng et al., 2002; Wu et al., 2009).

Hydraulic fracture apertures are usually determined in the laboratory by permeameter tests, with either gases or liquids being used to flow through fractured rock samples (Kling et al., 2016; Li et al., 2018; Shu et al., 2019; Zhang, 2018). In the field, hydraulic properties can be derived from hydraulic or pneumatic borehole tests (Aoyagi and Ishii, 2019; Jakubick and Franz,

1993; de La Vaissière et al., 2015; Shao et al., 2008). ~~For hydraulic field testing, many experimental designs are practicable that were already used in the Mont Terri URL, for example, hydraulic pulse, constant head or constant rate withdrawal tests using single, double or multi packer systems (Bossart et al., 2004; Martin et al., 2004; Meier et al., 2000; Yu et al., 2017).~~ Mechanical fracture apertures can generally be obtained by different fracture imaging methods, whereby visibility can be improved by injecting dyed or fluorescent resin into the fractured rock (Armand et al., 2014; Bossart et al., 2002). Seismic velocity measurements can be carried out in the laboratory by using ultrasonic pulse devices (Popp et al., 2008; Wild et al., 2015) and in the field, ~~for example~~ by applying mini-seismic methods (Schuster et al., 2017) ~~or by conducting interval velocity logs in boreholes (Martin et al., 2004; Schuster et al., 2001).~~ Geomechanical strength and deformation parameters are usually determined by laboratory experiments. For this purpose, many different test setups are utilized such as compressive strength tests, tensile strength tests, shear tests and triaxial tests under drained or undrained conditions. For the Opalinus Clay, numerous geomechanical tests were carried out on drill cores, primarily examining bedding anisotropy as well as the hydro-mechanical coupling by adapting the water content of the samples (Amann et al., 2011, 2012, 2017; Wild et al., 2015). In the field, handheld probes such as Schmidt hammer or needle penetrometer are used to estimate the uniaxial compressive strength and other mechanical parameters of rock material (Aydin, 2009; Buyuksagis and Goktan, 2007; Erguler and Ulusay, 2009; Hucka, 1965; Okada et al., 1985; Ulusay and Erguler, 2012).

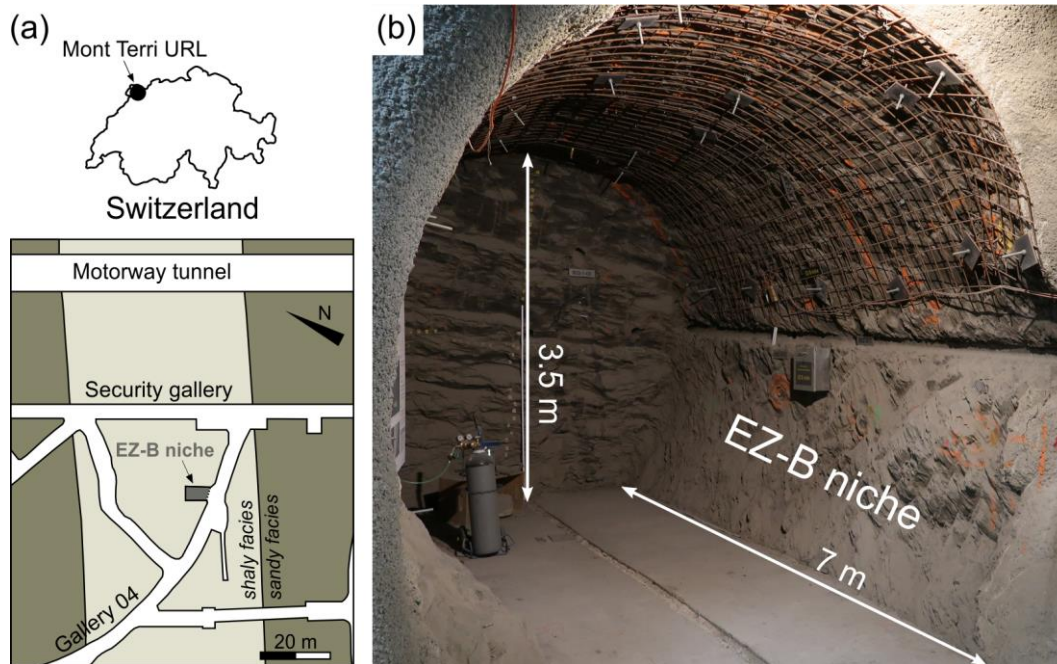
For most investigations drilling is required, either directly for performing borehole tests or for taking standard-compliant samples. However, drilling is not always feasible, ~~for example due to poor accessibility and because it is very time consuming and expensive. Furthermore,~~ and boreholes also affect the EDZ by creating additional fluid pathways. Core samples do not necessarily reflect the initial state as they can suffer from disturbance or damage during extraction and transport, leading for example to a change in water content. Hence, the objective of this study ~~is was~~ to investigate the hydro-mechanical properties of the EDZ in the Opalinus Clay of the Mont Terri URL ~~using on-site from in situ~~ measurements on the exposed rock surface. ~~In this study, We carried out a nondestructive and holistic determination of hydraulic and mechanical parameters of the fractured rock mass around a small tunnel niche-is conducted,~~ by ~~using a combining~~ transient-flow air permeametry, ~~a microscope camera photomicroscopy and a~~ needle penetration tests. ~~Beside the We characterized bulk rock properties of the claystone, and quantified mechanical and hydraulic apertures of different fracture types of the EDZ-are quantified and discussed in this study,~~ since these discontinuities can significantly control the overall material and flow behavior. ~~The presented methodological approach provides valuable information about the influence of the EDZ on the hydraulic and mechanical properties of the Opalinus Clay. Furthermore,~~ We have also explored the alterations ~~within the EDZ~~ of ~~the non-lined niche that was directly exposed to air for several years due to several years of direct air exposure of the rock surface are investigated and discussed.~~ By using the water content of the claystone, we compared the determined physico-mechanical parameters with data from other studies to assess the effect of desaturation directly on-site at the tunnel wall.

2 Material and methods

130 2.1 Study site

Fieldwork was performed in the EZ-B niche of the Mont Terri underground rock laboratory (URL) in St. Ursanne, Switzerland (Fig. 1a). The axis of the niche is oriented almost normal to Gallery 04 and to the minimum principal stress direction of the in situ stress field (Yong et al., 2010). The niche is located in the upper shaly facies of the Opalinus Clay, which consists of dark gray, mostly mica and pyrite containing calcareous silty-sandy claystones (Hostettler et al., 2017). Bedding is dipping 45 °
135 towards 150 °, thus the niche axis is oriented perpendicular to the strike of the bedding. As the URL is located in the southern limb of the Mont Terri overthrust anticline, the Opalinus Clay has experienced tectonic deformation (Nussbaum et al., 2011). As a consequence, pre-existing natural discontinuities, i.e. bedding-parallel tectonic faults, steeper splays and bedding planes, are present (Nussbaum et al., 2005). The EZ-B niche provides direct access to the overconsolidated claystone of the shaly facies of the Opalinus Clay and to the excavation-induced fracture network of Gallery 04. It was excavated from December
140 2004 to March 2005 by mainly road header and pneumatic hammering (Nussbaum et al., 2005). Numerous experiments were carried out in the niche, focusing for example on determining the extent and degree of damage of the EDZ (Schuster et al., 2017), fracture network analysis and small-scale mapping (Nussbaum et al., 2011; Yong, 2007), or long-term hydro-mechanical coupling processes (Möri et al., 2010; Ziefle et al., 2017).

Excavation-induced unloading joints (EDZ fractures) that are related to the construction of Gallery 04 are present within the
145 first 1.3 m ~~along~~ depth into the EZ-B niche (Nussbaum et al., 2005). Strike direction is mostly parallel to Gallery 04 and therefore perpendicular to the axis of the niche. At greater distances, artificial EDZ fractures that originate from the excavation process of the EZ-B niche itself are mainly oriented parallel to the sidewalls. In addition to the artificially induced unloading fractures, the EDZ also includes tectonic faults and splays, referred to as tectonic fractures. These tectonic fractures were reactivated by stress redistribution and convergence processes after the niche excavation and therefore show measurable
150 fracture apertures (Nussbaum et al., 2005, 2011). In contrast, tectonic discontinuities outside the EDZ are completely closed. In the entrance area of the EZ-B niche, the rock is partly covered by shotcrete, making a section of the EDZ inaccessible (Fig. 1b). The on-site measurements in the Mont Terri URL were carried out on 16–17 April 2019. At that time, the average air temperature in the EZ-B niche was 16.5 °C, while relative humidity was in the range of 67–72 %.



155 **Figure 1: (a) Location of the Mont Terri Underground Rock Laboratory (URL) alongside the security gallery of the Mont Terri**
motorway tunnel and the EZ-B niche situated in the shaly facies of the Opalinus Clay. (b) Photo and dimensions of the EZ-B niche,
where data acquisition was conducted. In the entrance area, shotcrete partly covers the rock surface on the left and right side wall.

2.2 Air permeameter

A handheld transient-flow air permeameter (model TinyPerm 3, New England Research Inc.) was used to measure the
 160 hydraulic aperture (a_h) of accessible fractures in the EZ-B niche. The working principle of the device was outlined by Brown
 and Smith (2013) and illustrated in Fig. 1 of Hale et al. (2020b). Further specifications are provided by New England Research,
 Inc. (2015). For each fracture, measurement was repeated at least three times. In case the mean absolute deviation of measured
 values was above 10 μm , the measurement was continued. Clear outliers were rejected in order to eliminate erroneous data,
 e.g. caused by fracture fillings (dust or loose material) or by leaks at the rubber nozzle tip of the air permeameter. Hydraulic
 165 fracture apertures are determined directly based on the time-dependent pressure equilibration and the internal calibration of
 the device (Brown and Smith, 2013; New England Research, Inc., 2015). Thus, no post-processing of data is required for the
 air permeameter.

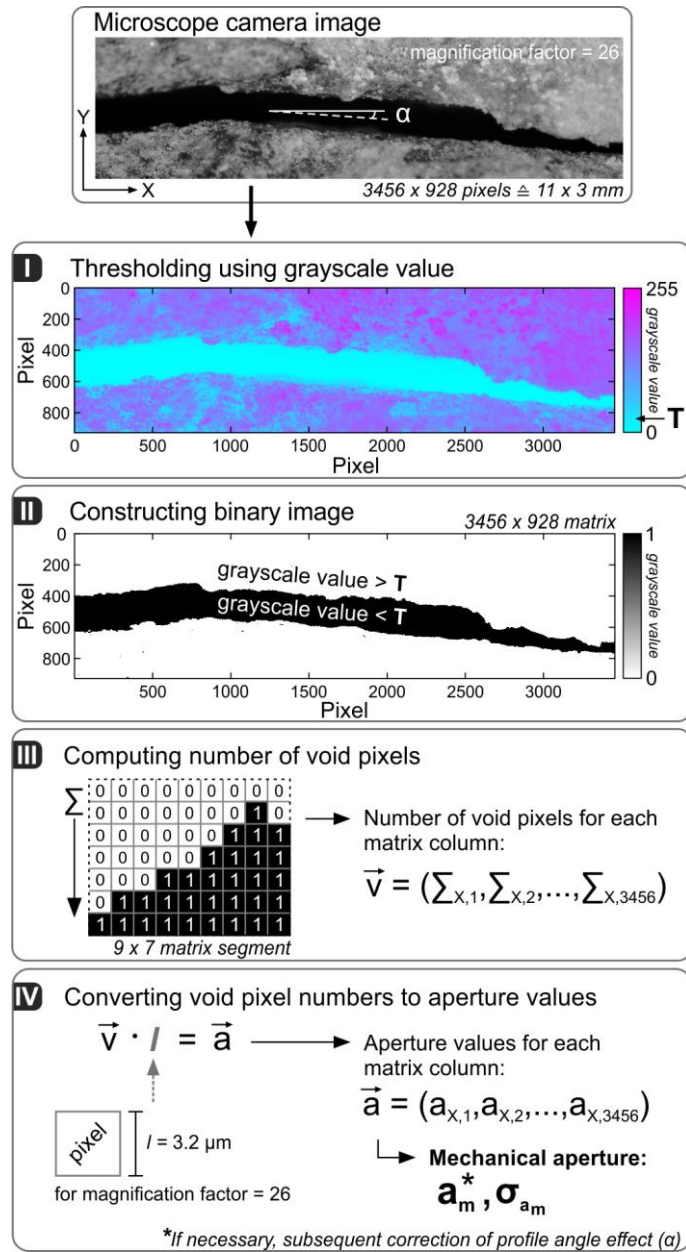
For most rocks, the hydraulic aperture derived from air permeameter measurements agrees with the hydraulic aperture available
 for advective flow. For sandstone, this was demonstrated by Cheng et al. (2020), where the air permeameter was validated by
 170 steady-state flow tests and different types of artificial fractures with apertures ranging between 7 and 62 μm . For all tested
 samples, hydraulic apertures were in excellent agreement with deviations below 5 μm (Cheng et al., 2020). Since clay minerals
 represent the main constituents of the Opalinus Clay (Bossart and Thury, 2008), diffusive double layers (DDL) are formed on
 exposed clay mineral surfaces in water saturated fractures (Soler, 2001), which could potentially reduce the hydraulic aperture

of fractures in argillaceous rocks. For the Opalinus Clay, the maximum thickness of the DDL is only 22 nm, which can be approximated by the Debye length (Wigger and Van Loon, 2018) using representative pore water ionic strength values (e.g. Pearson et al., 2003; Van Loon et al., 2003). Thus, in this case the DDL effect on a_h is negligible.

2.3 Microscope camera

For the same set of fractures (Sect. 2.2), high-resolution images of fracture traces were taken with a microscope camera (DigiMicro Mobile, dnt GmbH) in order to estimate mechanical fracture apertures (a_m) in the EZ-B niche. The digital camera, with an image resolution of up to 12 million pixels, comprises of a microscope with an adjustable magnification factor of up to 240. By adjusting the focus dial, the rock surface can be brought into sharp focus. Subsequently, the set magnification factor has to be recorded to evaluate the images. While taking the photo, the field of view should be aligned parallel to the fracture axis and the camera should look vertically into the fracture.

Microscope camera images can be evaluated both manually and automatically. The arithmetic mean of distances measured evenly along the fracture trace corresponds to the mechanical fracture aperture a_m , whereas the associated standard deviation (σ_{a_m}) provides a reasonable measure for fracture surface roughness (e.g. Brown, 1987; Kling et al., 2017). The manual evaluation method uses an image analysis software to determine the distance between the two fracture edges regularly along the imaged segment. For detailed description of the manual image analysis approach, we refer to Hale et al. (2020b). A minimum number of 20 distance measurements was needed to gain representative mechanical apertures. Additionally, an automatic approach for determining a_m and σ_{a_m} was applied in this study. The code for running the workflow in Fig. 2 is written in MATLAB (see Data and Code availability). As input data, microscopic grayscale images with specified magnification factors are used. For an applied image resolution of 9 million pixels, the resulting image size is 3456 pixels in x-direction. As the images should be cropped adequately before analysis according to the extent of the fracture void area, the image size in y-direction is variable (Fig. 2).



195

Figure 2: Workflow of the automatic approach for determining the mechanical fracture aperture based on microscope camera images of fracture trace segments.

The automated workflow is delineated in Fig. 2 and involves four steps. Based on the grayscale values of the image (0–255), a suitable threshold value T is first defined in order to segment the void area (region of interest) as precisely as possible. As a second step, the image is binarized, i.e. a value of 1 is assigned to the pixels of the void area and a value of 0 is assigned to all remaining pixels. Based on the resulting binary pixel matrix, the total number of void pixels (\vec{v}) is determined column-wise. In order to convert the number of void pixels into aperture values \vec{a} (in μm), the real length of one image pixel is required as

205 a conversion factor. The pixel length directly depends on the magnification of the microscope camera that was set when taking the photo. It can be determined by using the software PortableCapture (Hale et al., 2020b). Finally, the mechanical aperture of the analyzed fracture segment corresponds to the arithmetic mean of the computed aperture values in \vec{d} . If the fracture trace deviates from the x-direction of the image (denoted by angle α), a_m is corrected accordingly. Using a_m and σ_{a_m} , hydraulic fracture apertures a_h can be estimated subsequently by applying different empirical equations (Table 1).

210 **Table 1: Equations for estimating the hydraulic fracture aperture based on the mean mechanical fracture aperture and the standard deviation of measured distance values along a fracture trace.**

Reference	Equation
Kling et al. (2017)	$a_h \approx a_m \left(1 + \frac{\sigma_{a_m}}{a_m}\right)^{-1.5} \quad (1)$
Rasouli and Hosseinian (2011)	$a_h \approx a_m^3 \sqrt[3]{abs \left(1 - 2.25 \frac{\sigma_{a_m}}{a_m}\right)} \quad (2)$
Barton and de Quadros (1997)	$a_h \approx a_m \frac{1}{\sqrt[3]{1 + 20.5 \left(\frac{\sigma_{a_m}}{2a_m}\right)^{1.5}}} \quad (3)$
Xiong et al. (2011)	$a_h \approx a_m^3 \sqrt[3]{abs \left(1 - \frac{\sigma_{a_m}}{a_m}\right)} \quad (4)$
Renshaw (1995)	$a_h \approx (\bar{a}_m)_{Geom} \quad (5)$
Matsuki et al. (1999)	$a_h \approx \sqrt[3]{1 - \frac{1.13}{1 + 0.191 \left(\frac{2a_m}{\sigma_{a_m}}\right)^{1.93}}} \quad (6)$
Renshaw (1995)	$a_h \approx a_m \frac{1}{\sqrt[3]{\left(1 + \frac{\sigma_{a_m}^2}{a_m^2}\right)^{1.5}}} \quad (7)$
Amadei and Illangasekare (1994)	$a_h \approx a_m \frac{1}{\sqrt[3]{1 + 0.6 \left(\frac{a_m}{\sigma_{a_m}}\right)^{-1.2}}} \quad (8)$

2.4 Needle penetration test

A needle penetrometer device (Model SH-70, Maruto Corporation Limited, Japan) was used to determine the needle penetration index (*NPI*) of the Opalinus Clay normal and parallel to bedding, which is directly dependent on the strength of the rock (e.g. Ulusay and Erguler, 2012). For testing, the needle is pushed into the rock by manually applying a maximum load of 100 N. The quotient of the applied load and the attained needle penetration depth (in N mm^{-1}) corresponds to the *NPI* (Aydan et al., 2014; Ulusay et al., 2014). Needle penetrometer tests were carried out at different measurement points on the rock surfaces in the EZ-B niche. If microcrack formation around the needle hole or tensile splitting along bedding planes was observed, the measured value was excluded from the dataset. For detailed description of working principle and testing procedure we refer to the ISRM suggested method for needle penetration test by Ulusay et al. (2014).

Several physico-mechanical parameters are directly related to *NPI*. For example, a strong correlation between *NPI* and uniaxial compressive strength of intact rock was proved (e.g. Aydan, 2012; Uchida et al., 2004). Established empirical equations were used in this study to estimate uniaxial compressive strength (*UCS*), Brazilian tensile strength (*BTS*), Young's modulus (*E*), elastic P-wave (v_p) and S-wave velocity (v_s), cohesion (*c*) and friction angle (φ) (Table 2). In order to enable a direct comparison of the estimated parameters with existing literature data, the water content of the Opalinus Clay was additionally determined by oven drying according to DIN EN ISO 17892-1 (2015-03-00) using two representative rock specimens from the walls of the EZ-B niche, sampled at the time of the on-site measurements.

Table 2: Equations for the estimation of physico-mechanical rock parameters using the needle penetration index (*NPI*), taken from Ulusay and Erguler (2012), Ulusay et al. (2014), and Aydan et al. (2014). The relations are based on compiled experimental data obtained from various lithologies.

Parameter	Equation	Reference
Uniaxial compressive strength [MPa]	$UCS \approx 0.418 \cdot NPI - 0.004$	Uchida et al. (2004) ^a
	$UCS \approx 0.2 \cdot NPI$	Aydan (2012) ^b
	$UCS \approx 0.402 \cdot NPI^{0.929}$	Ulusay and Erguler (2012) ^c
Brazilian tensile strength [MPa]	$BTS \approx 0.02 \cdot NPI$	Aydan et al. (2014) ^b
Young's modulus [GPa]	$E \approx 0.05 \cdot NPI$	Aydan et al. (2014) ^b
Cohesion [MPa]	$c \approx 0.04 \cdot NPI$	Aydan et al. (2014) ^b
Friction angle [°]	$\varphi \approx 13.375 \cdot NPI^{0.25}$	Aydan et al. (2014) ^b
P-wave velocity [km s ⁻¹]	$v_p \approx 0.33 + 0.3 \cdot NPI^{0.5}$	Aydan et al. (2014) ^b
S-wave velocity [km s ⁻¹]	$v_s \approx 0.1 + 0.18 \cdot NPI^{0.5}$	Aydan et al. (2014) ^b

^a clay
^b mudstone, sandstone, siltstone, marl, lignite, tuff, soapstone, pumice, soft limestone, sheared shale
^c marl, siltstone, mudstone, tuff

In Ulusay and Erguler (2012), the term needle penetration resistance (*NPR*) is used instead of *NPI*.

3 Results and discussion

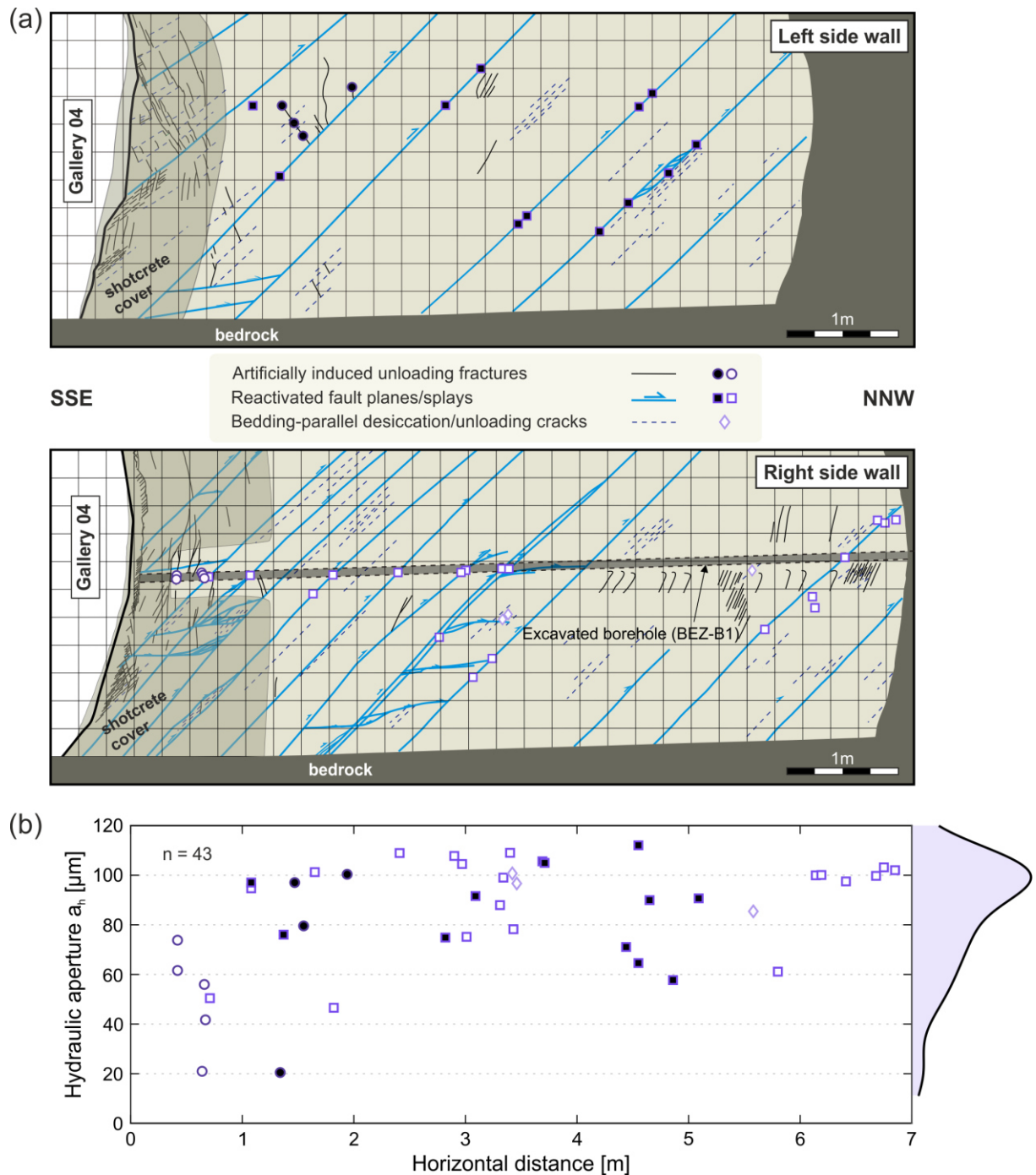
3.1 Hydraulic and mechanical fracture properties

3.1.1 Measured hydraulic fracture aperture

235 The hydraulic aperture a_h of artificially induced unloading joints, reactivated fault planes and bedding-parallel desiccation or unloading cracks of the EDZ in the EZ-B niche of the Mont Terri URL was determined at 43 measuring points on both side walls using the handheld transient-flow air permeameter (Fig. 3a). The mean hydraulic fracture aperture in the EZ-B niche was $84 \pm 23 \mu\text{m}$, with values in the range of around $100 \mu\text{m}$ occurring most frequently (Fig. 3b). On average, artificially induced unloading fractures (hereinafter referred to as EDZ fractures), mainly oriented sub-parallel to the axis of Gallery 04, 240 showed the smallest hydraulic apertures of $61 \pm 30 \mu\text{m}$ ($n = 9$) compared to reactivated fault and bedding planes. They were

also characterized by the largest range of measured aperture values from 20 to 100 μm , which is also evident from the high standard deviation.

Reactivated tectonic discontinuities, namely fault planes and splays of the SSE-dipping thrust system (hereinafter referred to as tectonic fractures), showed an average hydraulic aperture of $89 \pm 18 \mu\text{m}$ ($n = 31$). The hydraulic fracture aperture of bedding-parallel cracks was highest ($94 \pm 8 \mu\text{m}$), although the obtained average value cannot be considered representative due to a small number of measurements ($n = 3$). On the right side wall of the EZ-B niche, most of the sampling points were arranged near borehole BEZ-B1 (Fig. 3b) due to good accessibility and beneficial surface conditions. Based on the measured aperture values, no indication of a “borehole damaged zone” (Amann et al., 2017) is observable, which is related to the fact that the borehole BEZ-B1 is oriented perpendicular to the strike of the bedding.



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Figure 3: (a) Structural maps of the EZ-B niche with measurement points for hydraulic and mechanical aperture determination on the left (closed symbols) and right side wall (open symbols), modified after Nussbaum et al. (2005). (b) Hydraulic fracture apertures measured by air permeameter plotted against distance to Gallery 04. On the right side, the distribution of a_h is visualized by a probability density function obtained by Kernel density estimation (KDE).

255 The on-site aperture measurements in the EDZ clearly show that about 15 years after excavation, hydraulically open fractures
and therefore accessible fluid pathways are still present in the EZ-B niche. In the Opalinus Clay, fractures are successively
closed by self-sealing processes which lead to a significant permeability reduction in the EDZ, finally approaching the
hydraulic conditions of undeformed rock again (Bernier et al., 2007; Jaeggi and Bossart, 2014; Nagra, 2002). However, this
only applies for saturated conditions after backfilling and sealing, when progressive resaturation of the host rock around
260 underground facility is initiated (Bossart et al., 2017; Marschall et al., 2017). Under open conditions the EDZ is an unsaturated
zone, as for example shown by Ziefle et al. (2017). ~~On site measurements and numerical simulations confirm the evolution of
a seasonally influenced desaturated zone with an extent of about 50 cm as well as a long term influenced desaturated zone
with an extent of up to 2.2 m after 15 years (Ziefle et al., 2017). In the unsaturated EDZ in non lined niches, seasonal changes
of humidity and temperature inhibit self sealing processes.~~ Since 2006, the temporal evolution of the EDZ in the EZ-B niche
265 was assessed by jointmeter time series obtained from a single tectonic fracture. Based on this dataset, a cyclic long-term closure
of the monitored fracture was demonstrated (Ziefle et al., 2017), but this is probably primarily due to niche convergence.
For shales or argillaceous rocks, changes in the saturation state are directly linked to structural modifications (Valès et al.,
2004; Yurikov et al., 2019). In the highly saturated state, a large portion of the pore water is adsorbed onto the clay mineral
surfaces, while for high external suction, i.e. desaturation, it is extracted from the rock through the pore network (Zhang et al.,
270 2007). Dehydration of claystone leads to ~~a substantial modification of the pore size distribution and to~~ a decrease in total
porosity (Yurikov et al., 2019). ~~It also~~ and induces a reduction of pore and swelling pressure, which in turn impedes self-
sealing processes (Tsang et al., 2005; Zhang et al., 2007). In addition, secondary shrinking-induced tension fractures can
develop parallel to bedding with progressive dehydration, ~~especially if the exposed claystone surface was subject to multiple
drying wetting cycles~~ (Delage, 2014). In contrast, hydration of claystones leads to ~~an increase in total porosity and pore
pressure as well as to~~ a significantly enhanced creep and swelling capacity, ~~but it can also be accompanied by mineral
precipitation within the fracture network~~ (Yurikov et al., 2019; Zhang et al., 2007). In case of the non-lined EZ-B niche in
Mont Terri, self-sealing is inhibited due to a sharp decrease in water content of the rock mass close to the niche caused by
sustained ventilation since tunnel excavation. This observation is of particular importance for the second phase in repository
development, the open drift stage, where ventilation-induced damage and dehydration in the tunnel systems is also expected
280 (Tsang et al., 2005). The presented results therefore serve as a valuable analogue and provide information on the state of the
EDZ in a non-lined niche in indurated clay after prolonged exposure.

With increasing distance to Gallery 04, a general decrease in hydraulic fracture aperture a_h was expected. When leaving the
EDZ, the degree of damage or disturbance generally decreases as deconfinement, displacement and deviatoric stresses within
the rock mass are highest directly next to the cavity (Lisjak et al., 2016; Yong et al., 2010). Based on the results of the air
285 permeameter measurements, however, a weak positive correlation between a_h and the horizontal distance could be observed
(correlation coefficient $r = 0.43$). A decrease in hydraulic aperture with greater distance to Gallery 04 could not be observed,
since the fractures in the EZ-B niche originate from two different excavations. Due to the applied excavation technique and
favorable orientation of the niche (Sect. 2.1), the EDZ of the EZ-B niche is less pronounced compared to the EDZ around

Gallery 04. However, two EDZs, i.e. two fracture systems, are superposed. Hydraulic apertures in the immediate vicinity of
290 Gallery 04 are comparatively small (Fig. 3b). Presumably, this is caused by shotcrete application to the exposed claystone
surface associated with increased water availability, leading to partial re-saturation of the rock. This water supply most likely
promoted swelling of clay minerals and fracture closure to a certain degree, resulting in a general reduction of hydraulic
apertures in the entrance area of the EZ-B niche.

Due to the limited measuring range of the air permeameter, hydraulic apertures of widely opened fractures ($a_h > 2$ mm) could
295 not be quantified. Thus, the mean a_h of open fractures in the EZ-B niche was rather underestimated with this method. It is also
noticeable that for 49 % of the measurement points, the first measured value was smallest. This can be explained by dust or
loose material inside the fracture which was removed by the first stroke with the air permeameter. ~~In most cases, the first value
was therefore excluded from the data according to Sect. 2.2.~~ As outlined above and supported by continuously recorded
jointmeter data from the EZ-B niche, the saturation state ~~or moisture content~~ of the Opalinus Clay has a major influence on
300 measured fracture apertures. From 2015 to 2019, the investigated single fracture was subject to annual aperture fluctuations of
up to 500 μm . ~~This phenomenon is mainly related-~~ due to seasonal fluctuations of relative humidity (RH) (Ziefle et al., 2017).
However, over the long period since the niche was completed in 2005, the observed trend of cyclic aperture closure has
decreased substantially and seasonal fluctuations of fracture aperture are by now far less pronounced. ~~According to the long-
term monitoring of climatic conditions -~~ In the EZ-B niche, relative humidity is highest between July and October ($RH =$
305 100 %), while the lowest values are usually recorded in February ($RH \approx 60$ %). Since the measurement campaign for the
present study was carried out in April, it can be assumed that the obtained hydraulic and mechanical aperture values roughly
represent an annual average state of the continuously changing fracture system.

For the Opalinus Clay in the Mont Terri URL, no direct information on hydraulic fracture apertures is available, which further
illustrates the difficulty of conducting practicable and accurate a_h measurements in the field. In order to compare the measured
310 values with literature values in terms of plausibility, fracture transmissivities (T_f) obtained from extensive hydraulic testing in
the Mont Terri URL were utilized (Table 3). Based on the cubic law, an equivalent hydraulic fracture aperture ($a_{h,eq}$) can be
calculated from T_f using the relation (Brown, 1987)

$$a_{h,eq} = \sqrt[3]{T_f \cdot \frac{12 \cdot \mu_W}{\rho_W \cdot g}} \quad (9)$$

where μ_W is kinematic viscosity of water, ρ_W is density of water and g is the gravitational acceleration. It should be noted that
315 hydraulic tests are generally used to characterize certain borehole intervals. Transmissivity values that are derived from these
tests therefore relate to a certain rock volume, while the number of hydraulically active fractures intersecting the test interval
is usually unknown (Gustafson and Fransson, 2006). In this case, fracture densities must be considered for calculating
equivalent hydraulic apertures. However, some studies also provide single fracture transmissivities which could therefore
directly be converted to $a_{h,eq}$ using Eq. (9) for direct comparison with a_h measured by the air permeameter (Table 3).

320 **Table 3: Comparison of measured hydraulic fracture aperture (this study) with equivalent hydraulic aperture values derived from reported single fracture transmissivities from the Opalinus Clay in the Mont Terri URL.**

Reference	Description	Fracture transmissivity	Equivalent hydraulic aperture
Martin et al. (2004)	Transmissivity from high-resolution probe testing in four boreholes (EDZ + undisturbed rock)	$T_f = 1.0 \times 10^{-14} - 1.0 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$	$< 1-11 \text{ } \mu\text{m}^a$
Meier et al. (2000)	Single fracture transmissivity from long-term hydraulic testing (EDZ)	$T_f = 2.0 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$	29 μm
Bossart et al. (2004)	Single fracture transmissivity from hydraulic cross-hole testing (EDZ)	$T_f = 1.9 \times 10^{-8} - 4.0 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$	29–37 μm
Blümling et al. (2007)	Reported maximum local fracture transmissivity (EDZ)	$T_f = 5.0 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$	85 μm

This study	Air permeameter (EDZ)	–	20–112 μm

^a assumption of a single hydraulically dominant fracture (short test intervals, typically 5 cm)			

325 Although slightly larger, the hydraulic fracture apertures measured by air permeameter are in the same order of magnitude compared to equivalent hydraulic apertures that were derived from single-fracture transmissivity testing (Table 3). Due to the previously outlined processes related to the successive dehydration of the claystone, hydraulic apertures in the EZ-B niche were expected to differ slightly from the literature values due to the elongated exposure time. Nevertheless, the measured values are plausible and clearly show that the air permeameter is suitable for the measurement of hydraulic fracture apertures within the EDZ of the Opalinus Clay.

3.1.2 Measured mechanical fracture aperture

330 For the same set of fractures, the mechanical fracture aperture a_m was determined based on microscope camera images. For seven measurement points the mechanical aperture could not be evaluated due to poor quality of the microscopic images. The measured mechanical fracture apertures in the EZ-B niche showed a widespread range between 19 μm and 833 μm , while most values were clustered around 115 μm (Fig. 4). Artificial EDZ fractures showed the lowest values among the studied fracture types ($127 \pm 92 \text{ } \mu\text{m}$), whereas the mean mechanical aperture in the EZ-B niche was $233 \pm 205 \text{ } \mu\text{m}$. Again, no distinct trend with increasing distance to Gallery 04 could be observed. For the vast majority of sampled fractures, a_m was greater than or equal to a_h as expected (Fig. 4). As is the case for hydraulic apertures, almost no information on mechanical fracture apertures within the EDZ of the Opalinus Clay was available for comparison. Bossart et al. (2004) mention unloading fractures

with mechanical apertures of up to 1 cm. However, as the specified measurement range of the air permeameter is limited to hydraulic apertures of 2 mm, such widely opened fractures were not investigated in this study.

340

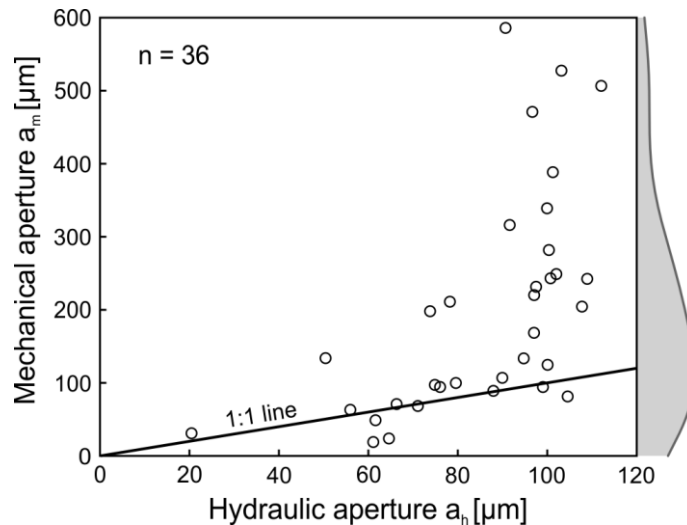


Figure 4: Comparison of measured mechanical and hydraulic fracture apertures in the EZ-B niche with probability density function of a_m . Two outliers with mechanical apertures of 789 μm and 833 μm are not shown for better visibility.

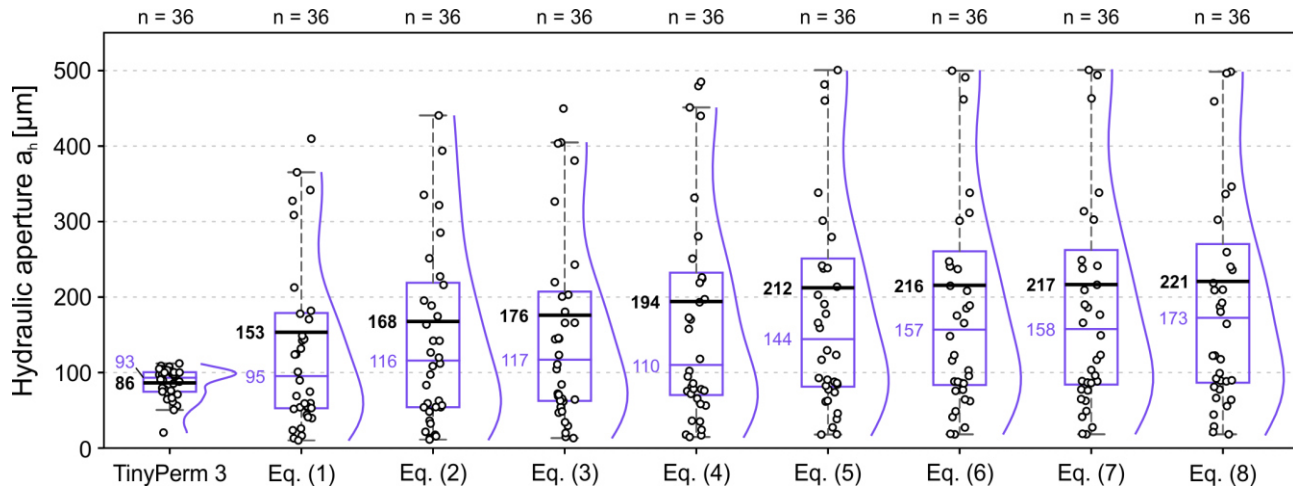
The newly implemented analysis algorithm for microscopic images (Fig. 2) provided similar results compared to the manual approach used in Hale et al. (2020b) (correlation coefficient $r = 0.93$). Thus, automatic image analysis is highly recommended. In addition to significant time savings, more representative results for a_m and σ_{a_m} of the imaged fracture trace segment can be obtained due to the large number of distance measurements. For images that could not be evaluated automatically, manual analysis was employed. This particularly applied to images that were not sufficiently focused or to fissures with very small mechanical apertures. In these cases, the void area could not be properly distinguished from the rock, thus hampering the selection of an appropriate threshold value for automatic analysis.

3.1.3 Estimated hydraulic fracture aperture

Based on the mean mechanical aperture (a_m) and the corresponding standard deviation (σ_{a_m}), providing a statistical measure for fracture surface roughness, hydraulic apertures were estimated using established empirical relations (Eq. (1) to (8), Table 1). For eight different equations, the results are shown in Fig. 5. With regard to the mean hydraulic fracture aperture, the full dataset of the discrete fracture network (DFN) in the EZ-B niche was best reproduced by Eq. (1) (Kling et al., 2017), which is therefore recommended for future studies. The median of this data set was also in excellent agreement with the measured data (Fig. 5). However, there were generally large deviations between the measured and estimated mean a_h . With regard to the frequency distribution of data points, Eq. (6) to (8) performed better because a_m is reduced to a lesser extent. Similar to the dataset of the TinyPerm 3 (air permeameter), most values were clustered around 100 μm . However, few very high values led

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360 to a significant overestimation of the arithmetic mean (216–221 μm). In order to provide a representative measure of central tendency of the estimated hydraulic aperture for a given fracture set or DFN, the use of the median is highly recommended. For EDZ fractures in particular, a_h was best estimated by Eq. (2) (Rasouli and Hosseinian, 2011).



365 **Figure 5: Comparison of hydraulic fracture apertures measured by air permeameter (TinyPerm 3) and estimated based on mean mechanical fracture apertures and standard deviations from microscopic fracture trace analysis. For each dataset, the arithmetic mean (bold black line), the median (thin purple line) and the probability density function (obtained by Kernel density estimation) is shown. Values above 550 μm are excluded from the graph.**

Higher deviations between estimated and measured hydraulic apertures were observed for fractures with either very low or very high mechanical apertures in relation to the measured value range. This was confirmed by a strong correlation between a_m and the resulting deviation between estimated and measured a_h values, for example, for Eq. (1) the correlation coefficient was 0.96. It was noticeable that for EDZ fractures a far higher agreement of estimated and measured hydraulic apertures could be observed in comparison to tectonic fractures, independently from the relation that was used for conversion. This is most likely related to smaller mechanical apertures. While EDZ fractures seem to better correspond to the general model concept of an “ideal plane-parallel fracture”, tectonic fractures are most probably characterized by a different a_m - a_h -relation. While implied by the presented measurement data, this issue should still be examined based on larger data sets.

Despite the good performance of the microscope camera method for EDZ fracture analysis, direct measurement of a_h with the air permeameter is always preferable. Nevertheless, the data derived from microscopic imaging can provide explicit information on fracture geometry and formation mechanism. Presumably due to their formation mechanism, EDZ fractures (artificial unloading joints) showed comparatively little variation in aperture along the fracture traces, resulting in a rather low mean standard deviation σ_{a_m} of 58 μm . For EDZ fractures, a_m was on average 1.7 times larger than a_h . In contrast, for tectonic fractures (reactivated fault planes), an average σ_{a_m} of 90 μm and a a_m/a_h ratio of 2.4 was determined in the EZ-B niche. However, the higher mean standard deviation for the measured aperture values along the fracture segment obtained for tectonic fractures is not necessarily caused by a higher roughness of the fault surfaces themselves. Namely, observations in the

385 Mont Terri URL showed that fault surfaces are generally polished with slickensides, while EDZ fracture surfaces often show
plumose structures (Nussbaum et al., 2005, 2011; Yong, 2007). On the other hand, since EDZ fractures originate from tensile
stresses, these fracture surfaces also show a high degree of matching. This directly leads to a comparatively small standard
deviation of measured aperture values along an imaged EDZ fracture segment. Fault planes in the EZ-B niche were reactivated
by stress redistribution during excavation and subsequent convergence, which is why the investigated tectonic fractures even
390 show measurable apertures. Due to shear loading, relative displacement led to a higher mismatch of the two fracture surfaces.
For the tectonic fractures, the higher mean standard deviation σ_{a_m} that was observed by microscopic image analysis therefore
primarily reflects the increased variance of measured distances due to mismatched fracture walls rather than the actual fracture
surface roughness.

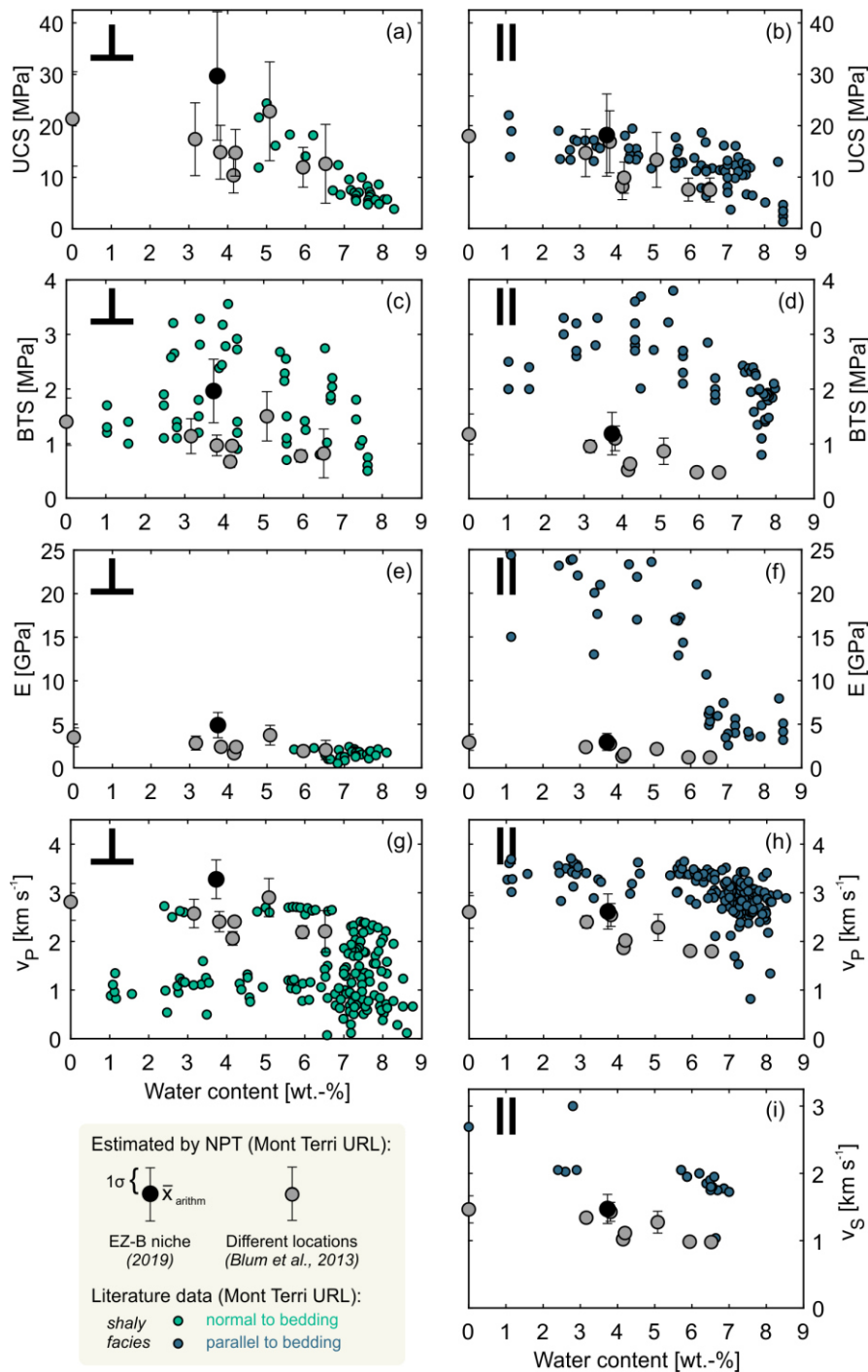
3.2 Geomechanical and geophysical properties

395 Needle penetration testing (NPT) was performed at 47 sampling points on both side walls of the EZ-B niche, including 18 tests
normal to bedding and 29 tests parallel to bedding. The measured needle penetration index (*NPI*) clearly confirmed the
significant strength anisotropy of the Opalinus Clay (Jaeggi and Bossart, 2014). Normal to bedding, strength was significantly
higher than parallel to bedding, indicated by a *NPI* of $98 \pm 29 \text{ N mm}^{-1}$ and $59 \pm 19 \text{ N mm}^{-1}$, respectively. For all measurements
a constant load of 100 N was selected. Thus, the *NPI* was only depending on the observed needle penetration depth.
400 Measurements normal to bedding resulted in several invalid tests due to formation of microcracks around the needle hole. In
this case, the measured value was discarded (Sect. 2.4). The results of the parameter estimation based on the measured *NPI*
are listed in Table 4.

Figure 6 provides a graphical overview and enables comparison with available literature data to assess the quality of the applied
in situ parameter estimation. As discussed in Sect. 1, geomechanical and geophysical parameters in the EZ-B niche are
405 significantly affected by the desaturation of the rock. Compared to the natural water content of the shaly facies of about 6.6 wt.-
% (Bossart and Thury, 2008), the water content of the Opalinus Clay in the EZ-B niche has decreased drastically to 3.7 wt.-%
due to direct air contact and long-time ventilation of the URL (Jaeggi and Bossart, 2014; Ziefle et al., 2017). Since samples
for water content determination were taken directly from the rock surface at the walls of the EZ-B niche, this value represents
the state of the Opalinus Clay after 15 years of direct atmospheric exposure. The *NPI*, and therefore estimated geomechanical
410 and geophysical parameters, are not influenced by the distance to Gallery 04.

Table 4: Estimated geomechanical and geophysical parameters for the Opalinus Clay in the EZ-B niche normal and parallel to bedding based on the needle penetration index.

Parameter	Normal to bedding	Parallel to bedding	Reference
<i>NPI</i>	$98 \pm 29 \text{ N mm}^{-1}$ ($n = 18$)	$59 \pm 19 \text{ N mm}^{-1}$ ($n = 29$)	
Water content	3.7 wt.-%		
<hr/>			
<i>UCS</i>	$29.7 \pm 12.5 \text{ MPa}$	$18.2 \pm 8.0 \text{ MPa}$	all UCS equations (average)
	$41.0 \pm 12.2 \text{ MPa}$	$24.8 \pm 8.1 \text{ MPa}$	Uchida et al. (2004)
	$19.6 \pm 5.8 \text{ MPa}$	$11.9 \pm 3.9 \text{ MPa}$	Aydan (2012)
	$28.3 \pm 7.7 \text{ MPa}$	$17.7 \pm 5.4 \text{ MPa}$	Ulusay and Erguler (2012)
<i>BTS</i>	$2.0 \pm 0.6 \text{ MPa}$	$1.2 \pm 0.4 \text{ MPa}$	Aydan et al. (2014)
<i>E</i>	$4.9 \pm 1.5 \text{ GPa}$	$3.0 \pm 1.0 \text{ GPa}$	Aydan et al. (2014)
<i>c</i>	$3.9 \pm 1.2 \text{ MPa}$	$2.4 \pm 0.8 \text{ MPa}$	Aydan et al. (2014)
φ	$41.8 \pm 2.7^\circ$	$36.8 \pm 2.8^\circ$	Aydan et al. (2014)
v_p	$3.3 \pm 0.4 \text{ km s}^{-1}$	$2.6 \pm 0.4 \text{ km s}^{-1}$	Aydan et al. (2014)
v_s	$1.9 \pm 0.2 \text{ km s}^{-1}$	$1.5 \pm 0.2 \text{ km s}^{-1}$	Aydan et al. (2014)



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Figure 6: Comparison of estimated geomechanical and geophysical parameters of the Opalinus Clay in the EZ-B niche of the Mont Terri URL (black symbols, this study) with literature data for the shaly facies, normal (a–g) and parallel (b–i) to bedding. In addition, a second NPT dataset of Blum et al. (2013) from various locations in the URL (shaly facies) is shown (gray symbols). Literature data (green and blue symbols) originate from other niches in the Mont Terri URL and are mainly adapted after Jaeggi and Bossart (2014) and references herein (the full list of source documents is provided in Appendix A).

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Based on the needle penetrometer data obtained in the EZ-B niche, the estimated uniaxial compressive strength (UCS) was 29.7 MPa for a water content of 3.7 wt.-% normal to bedding (Fig. 6a). For water contents below 4.5 wt.-%, no literature data on UCS is available for the shaly facies of the Opalinus Clay. Due to the fact that UCS is increasing linearly with decreasing water content (Wild et al., 2015), the estimated mean value can be considered reasonable and complements the literature dataset in Fig. 6a. The additional NPT dataset of Blum et al. (2013) also confirms the negative linear correlation of UCS and water content. Parallel to bedding, the estimated UCS of 18.2 MPa is consistent with literature data of the shaly facies for similar water content (Fig. 6b). The two NPT datasets, acquired from the EZ-B niche as well as different locations in the Mont Terri URL (Blum et al., 2013), exactly reproduce the trend that is evident from the available literature data. The estimated UCS values in Fig. 6a and b were obtained by using different empirical equations, leading to a comparatively high standard deviation. The individual results for each empirical equation are listed in Table 4. As needle penetration testing is widely used for estimating the UCS of rocks (Ulusay et al., 2014), several functions are available which have been deduced from various rock types (Table 2). For the Opalinus Clay, the applied combination of different established equations has proven to be suitable.

The Brazilian tensile strength (BTS) of the Opalinus Clay normal to bedding could also be estimated by the needle penetration tests. The mean value of 2 MPa that was obtained from the on-site measurements in the EZ-B niche is located approximately in the center of the literature value range for a comparable water content (Fig. 6c). Apparently, the literature data for the shaly facies is divided into two subgroups. Lower BTS values normal to bedding are most likely related to pre-damaged sample material, i.e. desiccation cracks, which preferentially form parallel to the bedding features in the drill core and therefore reduce the tensile strength of the tested sample perpendicular to bedding. Parallel to bedding, the estimated BTS deviates by about 2 MPa from the available literature data and is therefore underestimated (Fig. 6d).

Similar to UCS , the Young's modulus E is increasing monotonically with declining water content as evident from both literature data and the NPT dataset of Blum et al. (2013). For water contents below 5.7 wt.-%, no literature data is available for the shaly facies normal to bedding. As the derived Young's modulus of 4.9 GPa normal to bedding for a water content of 3.7 wt.-% was significantly higher than the available literature values for natural water contents (maximum of 2.4 GPa), the estimation was assumed to be applicable for the Opalinus Clay (Fig. 6e). With a mean value of 3 GPa, E was largely underestimated parallel to bedding compared to the available literature data ranging between 13 and 31 GPa for similar water contents (Fig. 6f). This is most probably due to the fact that rather well preserved drill core specimens are compared to the long exposed and highly damaged rock surface of a niche.

The elastic P-wave velocity (v_p) is slightly overestimated normal to bedding (Fig. 6g). Similar to Fig. 6c, two sub-datasets can be identified within the literature data. Here, pre-damage of the core sample material or an insufficient coupling of the ultrasonic source was most likely responsible for these reduced P-wave velocities, which are therefore not representative for the intact rock body (Jaeggi and Bossart, 2014). According to Jaeggi and Bossart (2014), the core samples belonging to the lower sub-dataset of literature values in Fig. 6g were partially penetrated by microcracks. The estimated v_p data seems to

represent the upper subset of the literature data. Since the needle penetrometer only samples a small area on the rock surface, the NPT is able to reflect the actual in situ conditions. Parallel to bedding, v_p is slightly underestimated but fairly represents the data range of the shaly facies (Fig. 6h). The observed trend of slight P-wave velocity increase with decreasing water content of the Opalinus Clay normal and parallel to bedding is also well represented by the datasets obtained from needle penetration testing.

For the elastic S-wave velocity v_s of the Opalinus Clay, a mean value of 1.9 km s^{-1} was estimated normal to bedding. Due to strong absorption and attenuation of wave energy and insufficient signal retrieval during ultrasonic velocity measurement (Gräsle and Plischke, 2010; Schnier and Stührenberg, 2007), only few literature data is available. For the shaly facies of the Opalinus Clay, Bock (2009) reports v_s values of 1.51 km s^{-1} for a natural water content of 6.4 wt.-%. Wileveau (2005) provides S-wave velocities of $1.45\text{--}1.58 \text{ km s}^{-1}$ for water contents varying between 2.4 and 2.9 wt.-%. Hence, normal to bedding v_s is most likely overestimated by the NPT. Parallel to bedding, a value of 1.5 km s^{-1} was determined. In comparison to existing literature data, v_s is underestimated in this direction (Fig. 6i). As ultrasonic velocity is explicitly dependent on the internal structure of the rock, such as cementation, anisotropy and porosity structure (Jaeggi and Bossart, 2014; Schuster et al., 2017), it can be assumed that the relationship of ultrasonic velocity and NPI is probably rather weak.

For the cohesion c and the friction angle φ , reliability of the estimated values (Table 4) could not be assessed due to limited literature data, especially for samples with low water contents. In Bock (2009), mean values for cohesion (3.7 MPa and 5.4 MPa) and friction angle (22° and 23°) of the Opalinus Clay for an average water content of 6.7 wt.-% are given normal and parallel to bedding, respectively. In contrast, Lisjak et al. (2015) used a cohesion of 24.8 MPa (normal) and 2.4 MPa (parallel) as an input parameter for their calibrated finite-discrete element model. The implemented friction angle of 22° complies with Bock (2009), but no information on the assumed water content is included. Cohesion values of 3.9 MPa (normal) and 2.4 MPa (parallel) derived from needle penetrometer measurements in the EZ-B niche were of the same order of magnitude as the data given by Bock (2009). However, the estimated friction angles of 42° and 37° normal and parallel to bedding, respectively, were significantly higher in comparison to the literature data.

Generally, the applied empirical functions performed better normal to bedding. The poor estimation of parameters parallel to bedding (apart from UCS) may be linked to unperceived (possibly micro-scale) shrinking or desiccation cracks, which preferentially form parallel to the bedding features (e.g. Amann et al., 2017; Schnier and Stührenberg, 2007). Microcracks would facilitate needle penetration, thus reducing the measured NPI as well as the estimated parameter values. It should also be noted that the existing empirical relations for estimating physico-mechanical parameters do not specifically apply to claystones or shales, but were derived based on compiled experimental data obtained for various types of soft rocks (Aydan et al., 2014). In addition to the factors mentioned above, sedimentary heterogeneity might also be responsible for geomechanical variability and the observed deviations between the NPI -based values and the considered literature data. However, heterogeneity of the shaly facies of the Opalinus Clay in Mont Terri is comparatively low (Jaeggi and Bossart, 2014). More likely, the observed deviations are due to variant surface constitution caused by the hugely varying exposure time of the rock

walls in the non-lined EZ-B niche in contrast to sampled specimens from drill cores. Although the measurements were conducted at the upper end of the specified application range of the needle penetrometer, physico-mechanical parameter estimation based on needle penetration testing can be recommended for indurated clays, especially for determining the anisotropic uniaxial compressive strength.

4 Conclusions

An excavation damaged zone (EDZ) in the Opalinus Clay of the Mont Terri Rock Laboratory, Switzerland, was characterized with regard to hydraulic and mechanical properties using three different methodological on-site approaches: (1) air permeameter, (2) microscope camera and (3) needle penetration test. About 15 years after excavation, artificially induced unloading joints (EDZ fractures), reactivated fault planes (tectonic fractures) and bedding-parallel desiccation cracks with a mean mechanical aperture of 233 μm and a mean hydraulic aperture of 84 μm were observed in the EZ-B niche, serving as potential flow paths for advective transport in the indurated clay formation. This is not only limited to the area of the strongly pronounced EDZ around Gallery 04, where a dense network of interconnected fractures is encountered, but also applies to potentially reactivated tectonic discontinuities at greater distances, e.g. due to large-scale stress redistribution or injection of fluids. After an initial continuous aperture closure observed by long-term jointmeter data records in the non-lined niche, which can be attributed to seasonally controlled shrinkage and swelling cycles in combination with niche convergence, this process seems to decelerate significantly after 15 years of monitoring. Locally, fractures are influenced by shotcrete application, leading to reduced hydraulic and mechanical apertures due to enhanced water availability and swelling of clay minerals in the immediate vicinity. Among the studied discontinuity types, the EDZ fractures showed the smallest hydraulic apertures. However, as 60 % of all measured values were within the range of 80–120 μm , a clear distinction was not possible. From direct measurement with the portable transient-flow air permeameter, plausible hydraulic aperture data could be acquired on-site, even if the entire range of fractures in the EZ-B niche could not be reproduced due to a limited measuring range. This means that the permeameter measurements tend to over represent smaller fractures. Here, indirect determination of hydraulic fracture apertures based on the automatic evaluation of high-resolution microscope camera images of fracture traces offers a practical alternative. Due to the smaller mean mechanical aperture of the artificially induced unloading fractures compared to the investigated tectonic fractures, conversion was most appropriate for the EDZ fractures. Tectonic fractures on average exhibit a higher variance of measured distances along imaged fracture traces, which can be explained by a higher degree of mismatch between the fracture surfaces due to the reactivation of fault planes during excavation. **However, the statistical significance of the observed differences between the different fracture types would have to be tested based on a larger dataset.** For specifying the mechanical aperture of a fracture network based on fracture trace micro-imaging, the median of measured values is most representative.

The needle penetration test proved to be a valuable tool, especially for accurate estimation of the anisotropic uniaxial compressive strength, as the needle penetration index satisfactorily reflects the in situ conditions of the intact rock mass. For

the shaly facies of the Opalinus Clay in the EZ-B niche, a mean uniaxial compressive strength of 30 MPa (normal to bedding) and 18 MPa (parallel to bedding) was determined. While parameter estimation based on needle penetration indices normal to bedding showed a high agreement with available literature data, physico-mechanical parameter values were mostly underestimated in bedding-parallel direction. Due to damage of the exposed rock surface associated with the formation of microcracks parallel to stratification, needle penetration was facilitated in this case. Due to direct air contact and ventilation of the rock laboratory, the desaturation of the claystone in the near field of the niche led to a sharp decrease in water content to 3.7 wt.-%, which is directly linked to an increased uniaxial compressive strength, Young's modulus and elastic P-wave velocity normal to bedding.

The applied on-site measurement methodology and evaluation approach provides a suitable instrument for the hydraulic and mechanical characterization of excavation damaged or disturbed zones in different geological environments, especially since drilling is not always feasible and the validity of estimated parameters is limited to the investigated location. With comparatively little effort, nondestructive analysis of time- and location-dependent variability of important parameters is permitted. Besides confirming the suitability of the methodological approach for flexibly determining hydraulic and mechanical properties, the study assesses the state of an EDZ in a non-lined niche after long-term exposure and therefore serves as an important guideline for diverse tunneling projects and future performance assessments of nuclear waste disposal sites in argillaceous rocks.

535 **Appendix A**

The literature data included in Fig. 6 (Sect. 3.2) were mainly taken from Jaeggi and Bossart (2014). This expert report offers a compilation of safety related rock parameters determined for the Opalinus Clay in the Mont Terri URL. All source documents for experimentally derived data on geomechanical and geophysical properties that were utilized in this study are listed in Table A1. Technical Notes (TN) and Technical Reports (TR) of the Mont Terri Project are accessible via <https://www.mont-terri.ch/en/documentation/technical-reports.html>.

Table A1: Source documents for experimental data on uniaxial compressive strength (*UCS*), Brazilian tensile strength (*BTS*), Young's modulus (*E*) and elastic P-wave (v_p) and S-wave velocity (v_s) of the Opalinus Clay (shaly facies) in Mont Terri.

Source document	<i>UCS</i>	<i>BTS</i>	<i>E</i>	v_p	v_s
Amann et al. (2011)	•		•	•	
Amann et al. (2012)				•	
Gräsle and Plischke (2010), TR	•	•	•		•
Gräsle and Plischke (2011), TN				•	
Jahns (2010), TN	•	•			
Rummel and Weber (2004), TN	•			•	
Rummel and Weber (2007), TN	•			•	
Schnier and Stührenberg (2007), TR	•				•
Soe et al. (2009)					•
Wild (2010) ^a		•			
Wild et al. (2015)	•	•	•	•	
Wileveau (2005), TR				•	•
Wymann (2013) ^a	•		•	•	
Zimmer (2012) ^a		•		•	

^a unpublished final theses, ETH Zurich, Switzerland

Code and data availability

545 All field data related to this manuscript and the MATLAB code for the evaluation of microscopic fracture trace images is available at <https://doi.org/10.6084/m9.figshare.12581144.v2> (Hale et al., 2020a).

Author contribution

SH, XR and PB carried out the measurements in the Mont Terri URL, DJ handled the organization and implementation of the field work. Formal analysis was done by SH and XR. PB supervised SH and XR and was responsible for funding acquisition.

550 SH wrote the initial draft and all authors (SH, XR, DJ and PB) discussed and interpreted the results and substantially contributed to editing and reviewing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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