Responses to comments by reviewer #1

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Received and published: 22 June 2020

Ref: SE-2020-76-RC1

The preprint paper "Measuring hydraulic fracture apertures: a comparison of methods" by Chaojie Cheng, Sina Hale, Harald Milsch, Philipp Blum deals with a comparison of three methods used to estimate the mechanical and hydraulic aperture of fractures under controlled lab conditions. The paper is well written, and the figures are nicely drafted and easy to understand. I think that this is going to be an important addition to the experimental literature aimed at quantifying fracture permeability with laboratory methods. I have some comments about the way the methods are presented and the context in which the results obtained are relevant. Some elaboration of the authors on the following issues might help strengthen the paper:

We sincerely thank Marco Antonellini 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 red. In addition, any changes regarding ''author responses to reviewer #1'' applied in the revised manuscript are also colored in red.

(1) The aperture measured at the surface of an outcrop might not have anything to do with the aperture measured at reservoir or aquifer conditions, because of the stress state at depth. This issue has always hampered the recognition of any validity of fracture aperture measurements from cores, lab experiments, or outcrops.

Response: We certainly agree with this fact which is (once more) also evident from Fig. 4. To recall, the main goal of this study was to compare hydraulic apertures determined with two portable methods to direct measurements using a flow-through apparatus. The comparison was performed for the same set of samples and at identical environmental conditions (ambient temperature and pressure). It is well understood that characterizing the hydraulic aperture of fractures at depth from measurements taken at the surface of an outcrop demands information on the mechanical response of a fracture to stress. This extrapolation will require the continued application of rock mechanical/physical devices like the one used in this study and measurements of the type displayed in Fig. 4. We have addressed this important point in ***Lines 43-47*** and also added corresponding statements in the conclusions section (***Lines 404-408***) that also relate to the second point in comment (2) below.

(2) The boundary conditions during a measurement made with the Tiny Perm might lead to a non-uniform sampling of the fracture and to erroneous results. For example, there might be gas slippage from the fracture at the end of the nozzle. In this case the permeability measurement is affected by an asymmetry of the flow field, so that the real hydraulic aperture of the fracture is not obtained. The fact that the different methods give similar results does not mean that they can be extended beyond the experimental conditions tested.

Response: We agree with both points. Regarding the first point we have clarified this issue in ***Lines 215-218***. Regarding the second point we have added a corresponding statement to the manuscript in ***Lines 404-405***.

(3) In the case of measurements made on fractures with smooth surfaces shut by the confining pressure, the instrument might read matrix permeability and not the hydraulic aperture of the fracture.

Response: The matrix permeability of the samples used in this study is in the order of 10^{-18} m^2 as derived from previous flow-through measurements (e.g., Blöcher et al., 2009; ***citation added in Section 2.1 and the list of references***). In contrast and at ambient pressure conditions, the respective permeability of all samples was measured to be at least two orders of magnitude larger than the corresponding matrix permeability. We agree, that fractures may close at elevated confining pressure and we have clearly stated the requirements for the applicability of the data evaluation procedure in the ***updated Section 2.2.1***.

(4) I find the statement in the conclusion "For such purposes, this study shows that the transient air flow permeameter offers a fast and highly efficient approach for accurate hydraulic aperture determination" very strong and a bit misleading. The number of samples tested and the experimental conditions (stress state, scale, and dimensions) are rather limited for such a strong statement. The air flow permeameter is as good as the calibration curve that allows to empirically correlate the pressure decay to the hydraulic aperture. Given the peculiar and heterogeneous flow field of the permeameter within the fracture, these empirical correlations are likely to vary a lot from sample to sample.

Response: This comment relates to Eq. (5) and the corresponding comment below. We agree that the number of samples tested and their length scale is rather limited. However, several types of single fractures (aligned, displaced, rough, smooth) were tested and the match between hydraulic apertures determined by the FTA and the TP was found to be very good (at corresponding pressure conditions). This result was obtained with a single calibration that relies on the parallel-plate assumption. Nonetheless, we have rephrased the corresponding statement accordingly in the conclusions section (***Lines 395-396***).

Some technical remarks:

Line 18 "...aperture differences between samples are merely reproduced qualitatively." I don't find this sentence clearly written.

Response: We have rephrased this sentence in ***Lines 18-19***.

Line 26 Also CO2 injection site characterization might benefit from your work…

Response: Agreed and added to the revised manuscript in ***Line 26***.

Lines 113-116 Some references would help making clear what you have done here.

Response: We have revised this paragraph for clarification and added three references in ***Line 129***.

Line 126 I would change the sentence like this: "...pressure profile through time measured by the instrument pressure transducer and flowmeters"

Response: We have rephrased the statement accordingly in ***Lines 142-143***

Eq. (5) $T = -1.5\log_{10}(a_{TP})+8.29$ Given the peculiar and heterogeneous flow field of the permeameter within the fracture, this empirical correlation is likely to vary a lot from sample to sample.

Response: This empirical correlation was originally derived based on measuring known fracture apertures between parallel-plate fractures. In this simplified case, mechanical apertures are equal to hydraulic apertures. In fact, the device works with this single empirical correlation to determine the hydraulic aperture of "natural" fractures. Thus, one main goal of the present work was to demonstrate whether this simple approach properly works on rough fractures deviating from the idealized case. To our knowledge, no validation and also no precision assessment have been performed on rough fractures yet. We have added one related statement in ***Lines 158-159***.

Line 165 Is this (a_h) consistent with the terminology used before?

Response: a_{TP}, a_{FTA}, and a_h all represent hydraulic fracture aperture. We used different notations to differentiate the results derived from different methods. a_{TP} represents hydraulic aperture measured with the Tiny Perm 3, a_{FTA} is the one obtained with the flow-through apparatus and a_h is derived based on the empirical correlations between hydraulic and mechanical apertures in Table 1. The notation (a_h) is therefore consistent with the terminology used throughout the paper.

Lines 224-225 These fractures are likely closed and the TP measures matrix permeability

Response: As mentioned before (comment 3), all fractures are open to a certain degree since the measured sample permeability is always significantly larger than the matrix permeability of these samples.

Fig. 7 What are the black dots in the graph above measurements FF2, FF3, FF4, and FOF4?

Response: We have updated the corresponding ***figure caption*** for clarification.

Line 262 Width or length?

Response: Here, the width of the fracture represents the fracture profile on the sample ends, which is equal to the sample diameter. In contrast, the fracture length is equal to the sample length. The term 'width' was therefore retained.

Fig. 9 What are the black dots above the boxplots?

Response: Same as Fig. 7. Again, we have updated the corresponding ***figure caption*** for clarification.

Lines 273-275 This sentence is not clear, please explain.

Response: We have revised the corresponding statements for clarification in ***Lines 321-324***.

Lines 338-339 "…the derived mean and…" This is not clear what it means.

Response: Conclusion (3) has been revised for clarification in ***Lines 389-391***.

Line 341 You talk about temperature in the conclusions but I am not sure you have investigated this in your experiments.

Response: Agreed. The statement has been deleted.

References added in the revised manuscript:

Blöcher, G., Zimmermann, G., & Milsch, H. (2009). Impact of poroelastic response of sandstones on geothermal power production. Pure and Applied Geophysics, 166(5-7), 1107-1123. https://doi.org/10.1007/s00024-009-0475-4

Brown, S., & Smith, M. (2013). A transient-flow syringe air permeameter. Geophysics, 78(5), D307-D313. https://doi.org/10.1190/Geo2012-0534.1 (was already cited in the ms)

Bruines, P. (2003). Laminar ground water flow through stochastic channel networks in rock, (Doctoral dissertation). Lausanne: EPFL.

Filomena, C., Hornung, J., & Stollhofen, H. (2014). Assessing accuracy of gas-driven permeability measurements: a comparative study of diverse Hassler-cell and probe permeameter devices. Solid Earth, 5(1), 1-11. https://doi.org/10.5194/se-5-1-2014

Ukar, E., Laubach, S. E., & Hooker, J. N. (2019). Outcrops as guides to subsurface natural fractures: Example from the Nikanassin Formation tight-gas sandstone, Grande Cache, Alberta foothills, Canada. Marine and Petroleum Geology, 103, 255-275.

Watkins, H., Bond, C. E., Healy, D., & Butler, R. W. (2015). Appraisal of fracture sampling methods and a new workflow to characterise heterogeneous fracture networks at outcrop. Journal of Structural Geology, 72, 67-82. https://doi.org/10.1016/j.jsg.2015.02.001 (was already cited in the ms)

Zeeb, C., Gomez-Rivas, E., Bons, P. D., & Blum, P. (2013). Evaluation of sampling methods for fracture network characterization using outcrops. AAPG bulletin, 97(9), 1545-1566. https://doi.org/10.1306/02131312042 (was already cited in the ms)