
Review by Robert Earon (specialist in hydrogeology at SKB, Sweden) (RC3):

- While I understand that this type of project involves a lot of collaboration and many parties and hence the length of the author list, it would be beneficial to briefly explain in the text the contributions of the various groups.

Response:
We thank the reviewer for raising this issue. According to the requirement of the journal, we will provide a statement of contributor roles (preferably adhering CRediT Taxonomy).

- Line 47-48: Surely if there is a plethora of research there can be more up to date references?

Response:
We have included additional references in the updated manuscript.

- Line 68: it is not certain that all readers will be familiar with all facilities. Countries or regions should be included in this list.

Response:
Addressed.

- Line 74: I'm unclear on what is meant here regarding tailored heterogeneity and complexity.

Response:
We revised with 'desired' instead.

- Line 156: Please elaborate on what is meant by semi-quantitatively.

Response:
We revised with 'qualitatively' to be precise.

- Line 158-159: this is a common effect of the Cubic Law. It would be beneficial to quantify this claim or provide a reference.

Response:
We are unsure whether the reviewer refers to 'A few highly conductive fault zones are responsible for the majority of the bulk water inflow in the tunnel.', or the previous sentence. In either case, it is based on our field observation, which is clarified in the revision. We are happy to provide further revision or explanation if the reviewer gives more specific information.

- Line 190-191: These pressure decay tests need a bit more explanation or a reference.

Response:
Addressed.

- Line 191: Please provide the in-situ hydrostatic pressure at the lab elevation (or groundwater level for reference)

Response:
There is limited information on the actual measured groundwater level in the vicinity of the Bedretto tunnel. Vlasek (2018) conducted relevant study and the estimated groundwater level directly above the Bedretto Lab (Tunnel Meter ~2000m) is 700-900m. We have revised the relevant text and provide the reference there.

Note: We group the following four comments here to respond to them collectively.

- Line 245 and Figure 2: this is probably one of the largest issues with the study, in that the 3 longest boreholes are all oriented in roughly the same direction. It is unsurprising that the fracture data is weighted to fractures and fracture sets which the boreholes would be geometrically more likely to intercept. Any claim regarding knowledge of the heterogeneity of fracture-related geoscientific data must be carefully examined in this light. Fracture data should be treated as inherently biased based according to the orientation of the boreholes, even when corrected.

- Line 410: I'm relieved that the authors have included this, but this should have been mentioned far earlier. Additionally, why was no effort made to correct for the bias? The authors mention that several fractures were found at acute angles to the borehole orientation, but what is the fracture intensity? These could be the fracture sets with highest true intensities.

- 414-415: the logical conclusion of this claim is that a borehole oriented orthogonally to the 3 existing boreholes would provide an entirely new data set and give a better understanding of the fracture matrix properties.

Response:
We thank the reviewer for pressing on this issue. Besides the three characterization CB boreholes, the short SB boreholes and the Bedretto Tunnel (shown in Figure 2) are orientated substantially different from the former. The SB boreholes and the tunnel, to some extent, sample fractures of certain orientations that could have been missed by CB boreholes. However, due to the limited lengths of SB boreholes, they probably are of local importance only. Additional boreholes with different orientations have been drilled since the completion of CB boreholes, which showed fracture sets and frequencies practically consistent with the CB borehole and tunnel mapping observations. More boreholes are planned to be drilled soon. We hope to address this issue with more confidence in the near future.

- 415-416: This claim needs to be carefully motivated. At present it lacks sufficient evidence to be included in the article.

Response:
We have tuned down this statement and noted the necessity of future work to verify this claim.

- Line 295: Is it possible that the change in the dielectric permittivity seen in the GPR survey could be due to mineral fillings such as graphite?

Response:
Indeed, all reflections arise from contrasts in dielectric permittivity and this could be either water-filled structures or mineral fillings. We have recently submitted a separate study where we combine borehole

televiewer data with the GPR reflections to assess this assumption, and found that the reflections are mainly driven by contrast in water and granite. We now refer the reader to this separate manuscript (please see comment below).

- Line 301-304: I think that readers would appreciate a more thorough interpretation of the GPR profiles. What are all the reflectors above the fault zone? Do they correspond with air reflections (i.e. through checking the geometry of the parabolas using) or do the parabolic shape and depth correspond with velocities in rock? What are the actual distances to the fault zones and do they correspond with your conceptual understanding of the site?

Response:
Thank you for pointing this out. We have now rephrased the geophysical-characterization section to address this comment and the one above. The newly added text reads as follows:

A more detailed study that combines GPR reflections and televiewer observations to delineate the geometry of the observed major fault, can be found in Shakas et al. (2021). By comparing televiewer observations to near-borehole GPR effects, the latter study also suggests that the observed reflections are primarily due to water-filled (open) structures (faults and fractures) and not to mineral-filled (closed) structures. We further notice that the GPR reflections match well the assumed geometry of the major fault and can further introduce constraints on the fault geometry further away from the boreholes.

The chevron type (V-shaped) pattern that the reflector (Figure 9) exhibits is a known ambiguity of borehole GPR surveys. This artifact is introduced by projecting the fault/fracture plane that intersects the borehole in 3D onto 2D space (Olsson et al., 1985). To overcome this issue, Hediger (2020) performed the correlation between the structures inferred from GPR reflections and ATV/OTV data, in an effort to delineate the major fault zones and fractures. Furthermore, several diffractions can be seen in the upper volume. These are most probably due to water-filled fractures/faults that are sub-perpendicular to the borehole trajectory (Grasmueck et al., 2010).

- Line 307-313: What are the length of the packers? How do you characterize connectivity? What are the durations of the tests and magnitude of the flow rates? I find the description of the hydrogeological testing methods needs considerable elaboration.

Response:
Thanks for the comments. The details are now added to the revised manuscript.

- The isolating part of the packers are one-meter long.
- The connectivity is analyzed by injection/production in one interval or borehole and checks the measurable pressure response in all others.
- The test flow rates are designed based on a preliminary estimate from a pulse test in the corresponding intervals in order to have (ideally) a maximum pressure change of 1 MPa to minimize geomechanical effects during the hydraulic testing.
- The duration of the flow or recovery test is set in such a way to observe infinitely acting radial flow.

- Line 317-319: What was the analytical method for analysis and why is this violated by the pressure gradient?

Response:
The methodology and criteria to analyze the flow test results as well as the assumptions are now described in more details within the manuscript.

- Depending on the pressure transient curve profile and the diagnostic plots, either Theis (Theis 1935) or GRF (Barker 1988) models were used to estimate the transmissivity and storativity of the tested interval/borehole. (as previously indicated in Table 2 notes)
- The isolated intervals in CB2 as well as the openholes (CB1, CB3) are assumed to be at steady state pressure before the start of the flow tests. However, this assumption, and therefore, the estimated transmissivities of individual boreholes have to be treated with caution, since these long intervals, in particular the open holes, include several conductive structures with non-uniform pressure headshead which might cause some cross flow between different structures within the same test intervals.

- Line 330: What was the corresponding head change and was pseudo-steady state achieved?

Response:
The pressure magnitudes in CB1 and CB3 changed by 0.2 and 0.4 MPa at the end of the flow period. The flow periods were long enough to observe infinitely acting flow regimes (for at least 1.5 log cycle after the wellbore storage effect subsides, as a rule of thumb). The flow test in CB1 did not show any boundary effect at the end of the flow period, whereas CB3 showed signs of an infinite linear constant head boundary at the end of the flow period. These details are now added to the revised manuscript.

- Line 335-344: It is unsurprising that the fracture network is heterogeneous and anisotropic. However, the times of responses are difficult to interpret without the estimated distance between the sections. It seems from Figure 9 that the boreholes intercept a major fault. Where are the sections with regards to the fault? The Structural geological information is absolutely vital in interpreting the results of the interference tests. Did you match the drawdowns against analytical solutions using i.e. Aqtesolv? How do the hydraulic properties compare with the ones of the packer tests? This could be vital in separating the near-field effects (closed fractures or fracture clusters which give high transmissivities during transient hydraulic tests) from the actual connected hydraulic properties.

Response:
The distance between all the packed intervals in CB2 to boreholes CB1 and CB3 are listed below for a better comparison of the hydraulic response time.

Table 1. Shortest distance with connecting feature between CB2 intervals with boreholes CB1 and CB3

	Shortest distance to CB1 (m)	shortest distance to CB3 (m)
Interval 1	23.8	60.4
Interval 2	23.4	59.9
Interval 3	21.4	50.7
Interval 4	23.6	45.4
Interval 5&6	18.1	29.1
Interval 7	17.1	30.3

The distances are estimated based on extrapolating and measuring the shortest fracture/fault between two intervals/boreholes. The shortest connection between CB1 and CB3 is also estimated to be approximately 29.7 m.

Based on the results of the GPR surveys, which are presented in Fig. 9, although the presence of a major cross-cutting structure that intersects all three boreholes (CB1,2,3) is evident from the survey, it is not fully comparable with the result from hydraulic tests. For example, the observed major structure from Fig. 9b intersects borehole CB2 at Interval 7, whereas results from hydraulic tests show strong hydraulic connection only between Intervals 5&6 in CB2 with borehole CB1, but not with CB3. This can be mainly attributed to the heterogeneities in the reservoir volume.

The analysis of all the transient pressure curves was carried out with the 'hytool' MATLAB Toolbox (Renard, 2017) with two models, Theis (1935) and Generalized Radial Flow (GRF) (Barker, 1988). The utilized toolbox uses analytical tools to fit the pressure transient profile with the selected radial flow models.

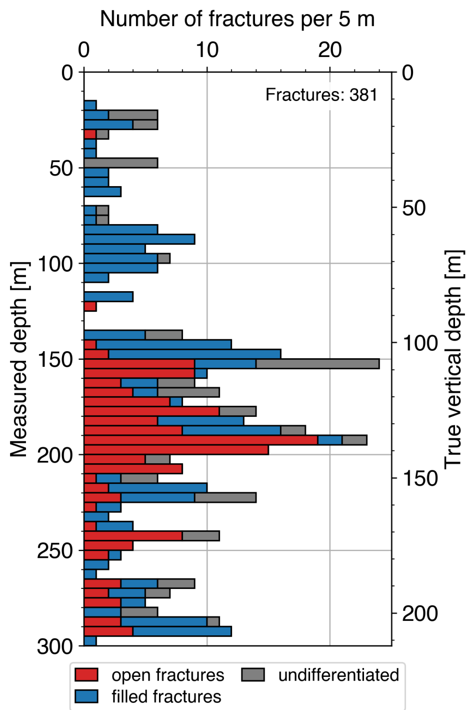
The manuscript is now revised accordingly at the corresponding sections.

- Figure 1: Please include a contour map. The topography is vital in understanding the placement and orientation of the tunnels and boreholes.

Response:
Here we refer to the work by (Meier, 2017). A simple but fundamental study regarding the effect of topography on the tunnel placement and stress state around the Bedretto Lab was documented there. This reference is already included in our paper.

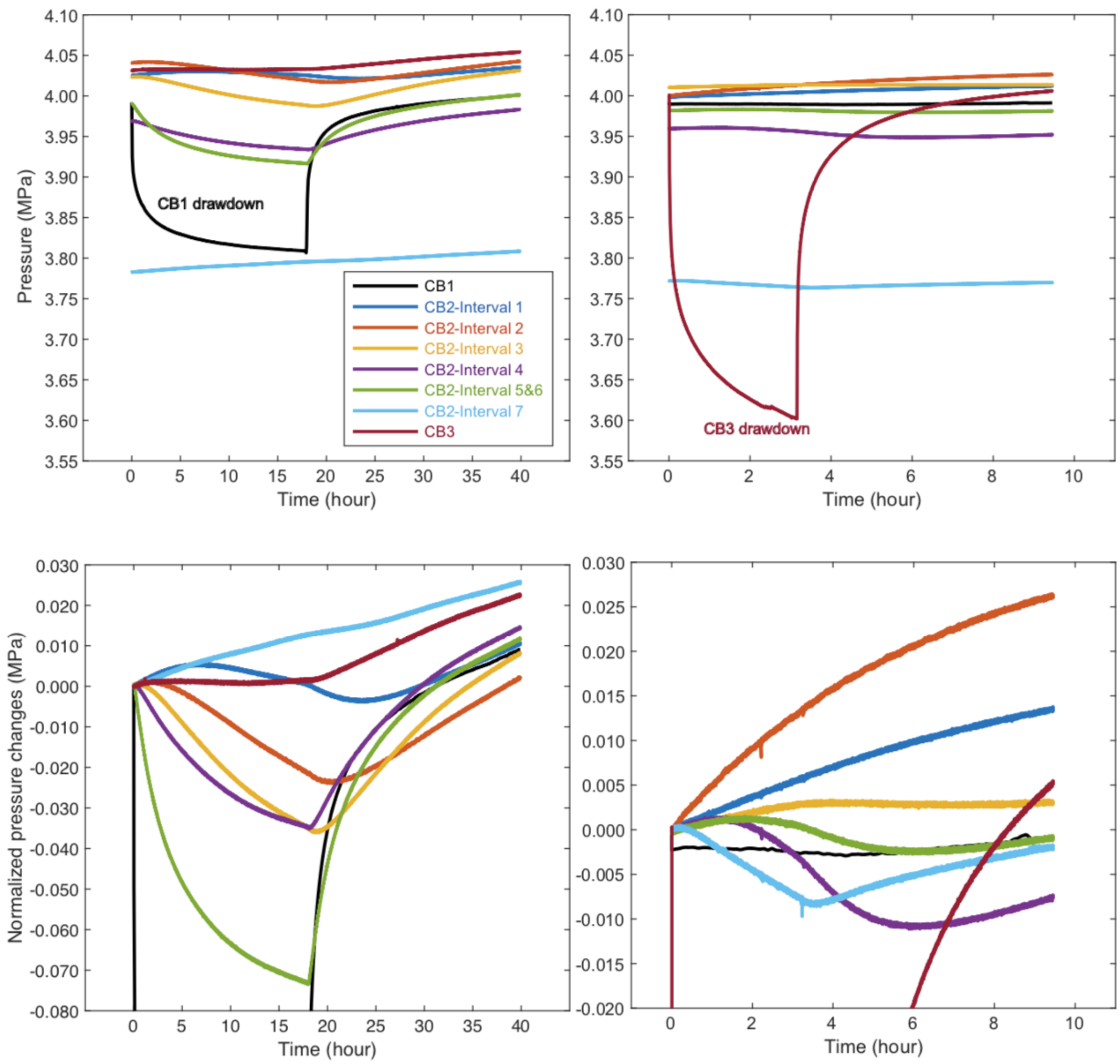
- Figure 4: Are all fractures treated similarly? It would be interesting to see the open vs. closed fracture count and perhaps plot major fault zones which were intercepted.

Response:
The following/attached fracture histogram shows three different fracture categories: open fractures, filled fractures (corresponds to closed fractures, these are generally infilled by biotite and/or quartz), and undifferentiated fractures. The last category represents fractures which cannot be identified with certainty whether they are open or filled. The major fault zones are represented by an increase of the open fracture count, and numerous with varying extent are intersected by the boreholes. The consistent picking of the fault zones, their classification, and correlation between boreholes is still ongoing and involves data sets that image the fault zones away from the borehole wall, e.g. GPR measurements. We will report the results in one of our upcoming publications.



- Figure 10: Please normalise this figure so that simply drawdown is shown. (Assuming either a water density or simply showing the change in pressure. CB2 interval 1 looks odd, and usually one isn't concerned with the absolute pressure in these types of tests.

Response:
Please see the figure attached below. The relative pressure changes are provided in a normalized fashion. This figure is included in the revised manuscript.



- 454-455: I'm not a rock mechanics expert, but I believe that given a reasonably stiff rock at depth dilation due to stress is mitigated by the rock matrix itself. However, in proximity to stress gradients like tunnels and the ground surface the effects will be far more prominent. I would suggest removing the claim regarding the weakening of the dilation concept.

Response:
Agree. We have toned down the statement there.

- Line 474: I think the word "apparently" is misused. However, I agree with the claim. Often the fracture core may have clay gouge, fillings etc which inhibit transverse flow.

Response:
Agree. We have revised this expression.

- Line 487: I'm unfamiliar with the term "hydraulic backbone"

Response:
The term backbone had been mainly used within the manuscript to refer to the dominant hydraulic pathway. For better clarity, the corresponding sentence now reads as: "Such heterogeneity is present both along individual boreholes and between boreholes, depicting complicated dominant flow paths within the rock volume."

- Line 492-494: I think the authors are correct, although the more care and perhaps a figure (in 3 dimensions) showing the hydraulic diffusivity of the sections and the location of the fault would make the point clearer. I believe the structure of the major zones is the underlying cause for the compartmentalization the authors indicate, but a bit more work needs to be done to really support the argument.

Response:
We appreciate the reviewer for pressing on this issue. Beyond the phase of this characterization work, additional boreholes have been drilled to allow for a more detailed mapping and hydraulic tests of the fractures/faults in the volume. The analysis is ongoing and we hope to report the latest in the near future, which could shed some light on this issue.

References

Bröker, K., & Ma, X. (n.d.). Estimating the least principal stress in a granitic rock mass: systematic mini-frac tests and elaborated pressure transient analysis. *Rock Mechanics and Rock Engineering*. https://www.research-collection.ethz.ch/handle/20.500.11850/466482

Meier, M. (2017). *Geological characterisation of an underground research facility in the Bedretto tunnel* [ETH Zurich]. https://doi.org/10.3929/ethz-b-000334001

Vlasek, A. (2018). *Deep structures of large toppling slopes at the Bedretto Adit (Ticino, Switzerland)*. ETH Zürich.