Review Dr. Richard Haslam

This paper bring together extensive characterization work undertaken at the BULGG in support of the FEAR project. The methodology and extent of characterization, as well as the rationale for fault selection is informative. There are clear citations to more specific aspects of the characterization.

Overall I enjoyed reviewing this paper and I am looking forward to seeing the results of the experiments.

Richard Haslam

Answer to Dr. Haslam

Dear Dr. Haslam,

Thank you for your kind assessment and the interesting comments and questions. We considered your comments as very thoughtful, which helped us to improve the manuscript. We put a major afford into rewriting some of the paragraphs, particular requirement 3 and explanation of the thickness constraint. Please, find our detailed statements below and the corresponding changes in the manuscript.

Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? - Need to check notation for "E-20" etc. unsure if this should be in full with superscripts.

- ➔ We adjusted to the exact values in m^2.

Line 10: *In what way is it persistent. is this its thickness or length or height?*

- ➔ Wherever we used persistent, we changed to spanning. This implies vertical and horizontal extension.

Line 137: *come back to this*

- ➔ Comment remains unclear.

Line 162: *Is there a reference for this calculation*

- ➔ Reference added and requirements rephrased.

Line 164: *for a fault patch of 1000 square meters I calculate a radius of approximately 17m not 30m.*

- ➔ Right the radius is 17, we intend the diameter of ca. 30 m, in fact later on we speak of extension of the fault patch of 30-50 m.

Line 165: *Reference here to Slip Tendency would be useful*

- ➔ Slip tendency is the ratio of resolved shear stress to resolved normal stress on a surface. We introduced the reference to Morris et al 1996 (Morris, Ferrilli, Henderson, Geology 1996:24; 275-278, doi: 10.1130/0091-7613(1996)024). Reference added.

Line 174: *But this may only be viable for 1 test if the fault stress is moved to another segment or patch along the fault. You state earlier that you plan multiple test. Can you provide classification around this point and what you will do if the reactivation transfer's the stress away from your test site?*

- ➔ One of the key elements of the project is conducting stress pre-conditioning via imposing stress changes on the fault to investigate the role of stress heterogeneities and criticality on rupture nucleation and propagation behavior. This stress manipulation is conducted via various injection and production scenarios in order to make sure that we have the ideal conditions for fault rupture.

Line 176: *what is this limit and how is it calculated?*

- ➔ Rephrased and clarified.

Line 179: *Is this thickness range compatible with your lateral extent constraints? Can you provide additional information on how this thickness constraint was calculated?*

- ➔ We added a brief description on the thickness constraints. A bit more detailed explanation here: The spatial dimensions of the fault zones, its maturity and its planarity are somewhat linked properties. These are likely the most controversial aspects of the siting as spatial predictability needs be trade-off against stress/strain field predictability, seismic potential and instrumentation requirements. As seen in databases of architectural elements of fault zones (FZ), the extension and persistence of FZ correlates with the amount of brittle deformation, hence the (cumulative) offset [Childs et al., 2009; Kolyukhin and Torabi, 2012; Torabi and Berg, 2011]. Using the empirical correlation, the selection is restricted to faults with a well-developed fault damage zone of at least a few dm and the total thickness results to more than one meter. Unfortunately, the empirical relations are based on a compilation that analysis mostly fault zone in hydro-carbon systems (sediments and sedimentary rocks). Therefore, ductile origin of most FZ in the Rotondo granite reduces their thickness [Lützenkirchen, 2002], which is accounted for by limiting the minimum size to about one meter. The upper boundary results from technical constraints of the instruments used for monitoring and the goal to monitor precursors as close as possible to the (re-)activated fault patch.

Line 180: *This requirement (3) needs to be rewritten. it is unclear and difficult to read. &*

Line 184: *Not sure this makes sense here. &*

Line 185: *What size volume are do you anticipate? &*

Line 186*: I don't understand what this sentence is stating and how it relates to the previous or next sentence &*

Line 188: *Can you explain this sentence in more detail. why is a wet or dripping fault suitable? What is it telling you about the fault in the tunnel? what do you expect to see away from the tunnel. How do you know that your injected volume of water and hence your pressure is not going to go straight out in to the tunnel. what if your reactivation disrupts the wall of the tunnel?*

- ➔ *Requirement 3 has been rewritten and shortened, addressing most other comments in this section. The rates of the pumps will deliver in the range of m^3/min. The water volume flow needed strongly depends on the "exact" permeability and porosity of the respective fault zone patch. The permeability restricts also the chance of pressurizing a sufficiently large patch of the fault zone. Simultaneously, it restricts the chance of depressurizing. Given that the tunnel is a 0-pressure boundary; experiments are conducted a few dekameters away from the existing tunnel and safety measures will be taken (by e.g. opening drainage holes close to the tunnel), we do not assume a rupture towards the tunnel.*

Line 298: *what is TM? is this tunnel marker? tunnel metre?*

- ➔ TM is “Tunnel Meter”, as now mentioned in 2.1. Additionally, we provide a list of abbreviations and symbols in the Supplementary Material.

Line 344: *This does not work with Figure 3j. Are these a sub-group of type 1? can these be shown in figure. From the text these sound like they are ductile reactivated type 1 faults. is that correct? are the kinematics different between the these two? you state that the "type 2" in your text is dextral but you dont say what the kinematics of your type 1 are.*

- ➔ The reference to Figure 3j was wrong and it has been deleted. These structures overprint Type 1 ductile shear zones (with reverse kinematics as specified at Line 337). A detailed description of the structural features can be found in Ceccato et al. (2024).

Line 351: *This is your type 2 in figure 3.*

- ➔ Thanks for pointing out the error. Figure 3 has been modified updating the right letter for the sub-figures.

Line 355: *figure 3k is titled for type 3 not type 4. your numbering is inconsistent with the figure.*

- ➔ Thanks for pointing out the error. Figure 3 has been modified updating the right letter for the sub-figures.

Line 375: *consistency in how you write these. Some places you have a space between TM and the number and in others you don't.*

- ➔ Thank you, it is corrected and used similarly everywhere now.

Line 378: *is there a reference or have you shown anywhere in this document what stress magnitudes are required for your experiment?*

- ➔ Based on a scenario evaluation of the slip tendency of the MC FZ the pore pressure needs to be increased by 6-10 MPa for making the fault (zone) slip. The information is added at the end of section 5.3.

Line 379: *How have you demonstrated that this is hydraulically connected?*

- ➔ It is a zone with a high fracture frequency, which is continuously wet to flowing in the tunnel. More detailed analysis at the tunnel wall may indicate a crossing point of maybe 3 different fault zones. Similar observations of fracture frequency and orientation have been made in the boreholes penetrating this zone at roughly 200 m depth below tunnel floor, which complicated the identification and correlation of the main faults between boreholes and tunnel.

Line 385: *A stereonet plot of this data would be helpful.*

- ➔ The main orientations are already shown in figures 6, 7 and 10. Adding another figure with a pole plot will in our opinion not increase the understandability. We rather think the stated “mean” orientations are easier to compare with surface measurements shown in Fig. 3.

Line 398: *move this paragraph to earlier where another comment asks about the in-situ stress*

- ➔ Section moved to the paragraph of your comment on line 378.

Line 419: *write these out in full*

- ➔ Full range provided now.

Table 1: *table does not fit page and is covering the page number*

➔ We resolve this during the editing process at SE by removing the page number.

Line 433: *in the table above this is given as >50m. why is it >100m here?*

➔ The difference is that a single fault zone patch should be > 50m but to allow for all experiments in the same fault zone, we need a fault zone which is "ideally" extending minimum 200 m in lateral direction. However, as a "pair" of experiments is planned, which should be compared, we can also work with 2 fault zones >100 m. With MC fault zone, we discovered a fault zone which can host all experiments.

Line 437: *I don't think this is the correct word here. Do you me "identified"?*

➔ The word "is" was not correct. The pre-cursor of the fault zone is of ductile nature. Thus, the faults "localized" at this ductile shear zones.

Line 542: *"indicated by 1" what? should this be Table 1?*

➔ "Table" added.

Line 610: *Add line break to distinguish this sentence from the above isotopic host rock bullet point*

➔ Done.

Line 614: *Given the predicted intersection of the MC fault with the DG would it not be worth spending some time characterizing this zone as it may have significant implications of the reactivation of both the MC and DG faults.*

➔ Good point. Based on this important intersection the decision was taken to perform a single experiment on that NE side of the Bedretto tunnel, which takes place some 20-30 m from the tunnel but >50 m far away from the intersection. All other experiments will be conducted on the SW side of the tunnel further increasing the distance to the intersection. Thus, the importance of characterizing the DG fault zone is of minor importance; Though, we agree it would be interesting if tests closer or at the intersection are considered at a later point.

Line 644: *The multiple interlinked planes has not been clearly demonstrated within this paper.*

➔ We partially agree with the Reviewer's comment, given that it is not possible at this stage to clearly demonstrate that the selected fault zone is composed of interlinked planes, how they are interlinked and at which distance. However, we based our conclusions on field observations at the surface, demonstrating that faults similar to the MC fault show a significant degree of interconnection between multiple planes (see green lineaments in Fig. 3 and the same lineaments reported schematically in the final model Figure 10). Further hydraulic tests and GPR logs are planned to improve the detail of the fault geometry.

Review Dr. Jamie Kirkpatrick

This paper presents an overview of the work that has gone into identifying a target fault for the "FEAR" project in the Bedretto Underground Laboratory for Geosciences and Geoenergies. The paper is essentially a review and synthesis of previous work over the past few years documenting the structural and geomechanical environment of the BedrettoLab. There are two main contributions in the paper: 1. To describe in as much detail as possible the characteristics of the target fault for an injection experiment and relate those to potential seismic behavior, and 2. to outline the decision process for identifying the target fault and demonstrating how the information from the previous studies was interpreted and used to justify that decision. The first contribution is dealt with very well in the manuscript, but I think the authors could consider how they can use Discussion section of the paper to better inform the community about the relative value of the survey datasets to the decision-making process to make sure this is a paper that can be useful to a broad audience.

Overall, the scientific significance is excellent because this synthesis of data describing a fault structure is exceptionally detailed and the inferences drawn regarding the geometry and mechanical and hydrological properties will be tested with the planned injection experiment.

The scientific quality, is excellent. Much of the primary data has been reported previously, but the description of the methods and their uncertainties and treatment of those uncertainties in the interpretation is very good.

The presentation quality is also excellent. The paper is well written and the figures are generally high quality and useful. The text uses some jargon associated with the BedrettoLab project, which I suggest clarifying for a general audience (see minor comments below), but is mostly accessible.

Answer to Dr. Kirkpatrick

Dear Dr. Kirkpatrick,

Thank you for your kind and thorough assessment, comments and questions. We considered all your comments and questions, which improved our manuscript. We put some afford into rewriting sections 1,3 and 6 but did not short tremendously as we estimate most of the information valuable for a broad interdisciplinary audience. Please, find our detailed statements below and the corresponding changes in the manuscript.

Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Abbreviations need explaining in places

- ➔ We provide a list of abbreviations and symbols in the Supplementary Material.

Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? Minor clarifications suggested below. There are some sections that could be shortened without loss of content (Sections 1, 3, 6)

- ➔ As much as the contribution is an interdisciplinary effort, we expect that the audience will be interdisciplinary. This implies, that we need to set the stage, explain the methods and integrate the results across the touched disciplines to make the results and its implications accessible to the audience. Thus, we agree and conducted a limited rephrasing/shortening for concise language but we disagree to shorten dramatically the sections 1, 3 and 6.

Specific Comments

Introduction mainly focuses on the scope of the FEAR project, but I suggest re-focusing some of the material in the second half of the introduction onto an explanation and justification for this study. Why is knowledge of the fault important? What fault characteristics are expected to be relevant and why?

➔ We rephrased and shortened the introduction (see also answer to your main comment).

It may be too late to reconsider this, but the name "FEAR" for a project that seeks to deliberately cause an earthquake is a potentially difficult choice for e.g. outreach and public awareness efforts.

➔ The acronym has been defined during the proposal phase for the ERC grant and is well-established now that the project runs in its 3rd year. Thus, we see ourselves unable to change it.

Section 3: In point (1) Geometrical… have the authors been able to consider proximity to nearby faults in their list of fault properties? This is an important factor for mitigating potential triggering effects of a stimulated earthquake.

➔ Yes, the proximity to nearby faults has been considered, and actually no major lineaments, either ductile or brittle to ductile have been observed for the 50 m before or after the selected fault. Only minor brittle structure with no evidence of movement have been detected towards N of the fault.

Section 5: I suggest the authors consider adding some detail of the degree of linkage of the different structures/sets/types as this could affect the total dimension of fault that may rupture. This is particularly important as the tip line of the MC fault has not been found so there is only a minimum bound estimate of the full dimension of the fault.

➔ We do not have any constrain on the degree of linkage of the different structures other than the results from remote sensing, showing that Set(1) structures are the most persistent at all scales, and the MC fault-type lineaments are composed of shorter segments at the scale of the fault/deformation zone. Further analyses of the fracture network would be required to provide other constraints, and this goes beyond the scope of the present paper.

Line 114: can you include the slope of the tunnel (i.e. plunge) in this brief description of the tunnel attitude?

➔ Yes, added "with a slope of .002-0.017 towards Ronco Portal"

Line 126: Explain the terminology used for TM2805 etc. (what is the refrence frame for these values) – this could be done in the caption to Fig 1b.

➔ TM is "Tunnel Meter", as now mentioned in 2.1 with additionally providing the reference scheme as start and end of the tunnel (TM0 to TM5221). Additionally, we provide a list of abbreviations and symbols in the Supplementary Material.

Line 145: Check the figure calls here – type 2 structural orientations are in Fig 3k, whereas type3 orientations are in Fig 3j

➔ We have modified and corrected the references to Figure 3 throughout the text (as well as in the figure caption) to match what is reported in the sub-figures.

Line 440: which side of the fault moved toward the SE?

- ➔ The movement indication refers to the hanging-wall of the fault (northern block, top). Text modified accordingly, specifying the side of the fault which moved.

Line 453: what is "BFE_A05" etc?

- ➔ BFE_A… is the borehole identifier consisting of borehole ("B"), the experiment ("FE" for FEAR), the drilling campaign ("A") and the borehole number. We added this to the abbreviations list in the appendix.

Line 497: why is the "anastomosing fault and fracture plane" geometry not shown in Fig 10?

- ➔ We thank the Reviewer for pointing out this unclear sentence. The "anastomosing" adjective was meant to refer to the overall geometry of the deformation zone, resulting from the superposition of two classes of fractures and fault planes differing in strike by 20-30 °. We have now modified the text specifying this point.

Line 523: specify which elements of the approach specifically brought the most value so that future projects can benefit from these lessons.

- ➔ This is a good question to which possesses no simple answer. Each step of the siting process requires a certain combination of techniques. Remote sensing and surface geological work is important to understand the geological framework. Geophysical measurements are important to estimate the 3D geometry of the faults and compare to outcrop scale. Detailed mapping and core analysis are important for delineating the single fault and parametrization, which is alimented by hydraulic observations and tests. In turn, these are of high importance for the lab tests and the geomechanical analyses, which also constrain the fault selection. We expand on this in the manuscript.

Line 551: are the faults at 48 and 49 in figure 7 not principal slip planes? Is there any constraint on the offset across the MC fault?

- ➔ Faults 48-49 are the local principal slip planes, which might have been developed by limited shearing on pre-existing structural discontinuities. Unfortunately, we have no constraints on the offset across the MC fault.

Figure 1: Explain the contacts between rock types on the map in the legend or caption. Why are the traces of faults at the surface in B not shown in A also?

- ➔ Figure 1a is meant to be a geological sketch of the area presenting the main tectonic units; at this scale it is not possible to represent all the tectonic lineaments with sufficient detail. We have now improved the figure accordingly to explain the contacts between rock types.

The MC fault is not defined in the text until Section 5.3, so references to MC fault in the captions to Figures 3, 4, 5 are confusing.

- ➔ The term "MC fault zone" is now introduced at the end of the introduction already and in the caption of figure 2.