Solid Earth Discussions

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Comment on se-2021-39

Anonymous Referee #3

Referee comment on "Micromechanisms leading to shear failure of Opalinus Clay in a triaxial test: a high-resolution BIB–SEM study" by Lisa Winhausen et al., Solid Earth Discuss., https://doi.org/10.5194/se-2021-39-RC3, 2021

General Comments

The authors present a thorough and high resolution study of the deformation mechanisms associated with the Opalinus Clay using a combination of triaxial tests and post deformation image analysis. The study builds on previous work, but presents a new set of data which will be highly valuable to the community, and for that reason, in my opinion, it deserves to be published. However, there are some scientific questions/comments which I would like to see addressed before the MS is accepted for publication, which I present in the specific and technical comments below. In addition to these I have three main comments:

- The authors should consider the role that mechanical anisotropy has on their results. It is mentioned briefly in the introduction, but then very little attention is given to this thereafter. I feel that some of the observations, for example the orientation of tensile cracks being oblique to the loading direction, could be explained by the mechanical anisotropy present within the material. I have suggested some studies which the authors may find useful on the subject.
- There is an inconsistency when describing the orientation of structures or processes, where the authors use the sample orientation, bedding orientation and loading orientation throughout. I found this confusing when reading the MS and I would recommend that the authors use the bedding orientation only. There is one point (which I highlight below) where it is also appropriate to refer to structures/processes relative to the loading direction as well, but apart from that I would just stick to bedding orientation.
- At the end of the MS the authors run the risk of undermining their own great work by suggesting that their results do not compare well with naturally deformed samples of OPA. This may be the case, but then you need to stress why your contribution is still valuable, and give more details on why you think there are differences, and what can be done in any further work. The authors give a vague answer to this, but I would suggest that they end on a stronger note.

Apart from the inconsistency mentioned above, the MS is in the main well written, with a

good structure and relevant (and useful) figures. There are some typos and minor technical amendments which I suggest in the detailed comments below.

I wish the authors the best of luck and I look forward to seeing this work published soon!

Specific and Technical Comments

Line 18 – Why test at this orientation? This is also a general question, not just specific to this line.

Line 28 – Could you briefly state what the major effect on permeability evolution is in the abstract?

Line 51 – Are the bedding parallel cracks likely to exist at depth? Or are they only present on exhumed material that has therefore been unloaded? This may be pedantic but the way this reads at the moment suggests that these exist at depth, like the pore space in the fossils, pyrite or clay matrix (which all presumably exist at depth).

Lines 61-64 – There has been a renewed interest in looking at failure in shales at different orientations see the following papers:

Nejati, A. Aminzadeh, F. Amann, M.O. Saar, T. Driesner (2020) Mode I fracture growth in anisotropic rocks: Theory and experiment. Int J Solids Struct, 195 pp. 74-90, 10.1016/j.ijsolstr.2020.03.004

Gehne S, Forbes Inskip ND, Benson PM, Meredith PG, Koor N (2020) Fluid-driven tensile fracture and fracture toughness in Nash point shale at elevated pressure. J Geophys Res: Solid Earth 125:1–11. https ://doi.org/10.1029/2019J B018971

Forbes Inskip ND, Meredith PG, Chandler MR, Gudmundsson A (2018) Fracture properties of Nash Point shale as a function of orientation to bedding. J Geophys Res: Solid Earth. https ://doi. org/10.1029/2018J B0159 43

Chandler MR, Meredith PG, Brantut N, Crawford BR (2016) Fracture toughness anisotropy in shale. J Geophys Res: Solid Earth 121:1–24. https ://doi.org/10.1002/2015J B0127 56

Although these studies mainly use unconfined tests, they demonstrate how the fabric, and alignment of grains in shales has a significant effect on fracture propagation and mode of failure. Although I do not think an in depth discussion of these papers is required, they should at least be mentioned here.

Line 86 – What is the range of confining stresses tested? You quote the strain range (>20%) so you should also quote the stress range.

Line 99 – This should be "gouge" not "gauge"

Line 101 – I don't think "modelled experimentally" is the best phrase here, perhaps "has been analysed experimentally by use of direct shear tests on samples sheared both parallel....."

Line 128 – Why did you choose to core the material in this orientation? Are your tests on samples in this orientation the most representative of what you would expect on structures found at Mont Terri and elsewhere in the OPA? As you mentioned earlier, and in the references I provide above, loading orientation is known to be a significant contributor to failure (fracture mode, strength etc) in transversely isotropic rocks. It would be good to show the reasoning for your sample orientation choice here.

Line 134 – Similar to my comment above, why did you choose a circumferential displacement rate of 0.08 mm/min. Many failure processes are heavily rate dependent, are these rates relevant to the application of your study? Or is this rate defined in an ISRM suggested method?

Line 139 – This section relates only to sample preparation for the image analysis, and so should be titled as such. Something along the lines of "Sample preparation for image analysis". Furthermore, I would also change section 2.1 to something like "Material description and core sample preparation" or "Material description and sample preparation for mechanical testing" if you want to keep the two types of sample preparation separate. Either that or you could remove lines 126 – 130 from section 2.1 and incorporate it with section 2.3 for a more general sample preparation section, but this should then come before the section on Triaxial testing.

Line 153 – Do you really need to use the acronym ROI for regions of interest? I do not think it saves much in the way of words, and in my opinion the use of another acronym is confusing for the reader. You also only use it once in the whole MS.

Line 163 – I would use either sub-horizontal or parallel to bedding, and not both. My preference would be to always use an orientation related to the bedding, so parallel in this case. The reason being that the bedding relates to the fabric of the rock and will remain (relatively) constant, whereas horizontal or vertical can be different depending on how you orientate your sample. Also be consistent then with how you define both fracture sets, i.e. oblique to bedding (fracture set 1) and parallel to bedding (fracture set 2).

Line 205 – This should be "saddle reef pores" rather than "raddle reef pores" I think. I have to admit, this is not a term I am familiar with. Do you need to define this, or at least annotate examples in Figure 7?

Lines 211 – 214 – It is not clear to me where these porosities have been measured. Could the sub-areas used in this analysis be marked on Figure 7?

Lines 219 and 224 – I think you have mixed up fracture sets 1 and 2 here. In section 3.1 you define fracture set 1 as the set oblique to bedding while fracture set 2 is parallel to bedding. Please amend to be consistent.

Line 226 – Here you go back to defining features from the horizontal rather than bedding. Switching between the two is confusing, so please stick to one or the other. As mentioned previously I think orientating with regards to the bedding is better.

Line 230 – Further to my previous comment: You now use the bedding direction rather than horizontal. You use both within the same paragraph, please be consistent.

Lines 233 – 234 – "In general, the deformation of both the clay-rich matrix and larger quartz, calcite and mica grains is brittle, ductile or a combination", brittle, ductile or a combination covers everything and so this sentence in its current form is rather redundant in my opinion. I understand what you mean, in that you do not just have one type of deformation and that both occur, but maybe then consider re-writing the sentence to something like "We observe both brittle and ductile deformation in the clay-rich matrix and larger quartz, calcite and mica grains, and so deformation is not solely brittle or ductile."

You also list clay-rich matrix, quartz, calcite and mica here, what else is there of significant quantities? Do you not see deformation in the Iron rich minerals and/or feldspars? If not is this because they account for <10% of the rock (from section 2.1.), and therefore could this simply be a sampling bias? I just wonder if you need to

specifically list clay-rich matrix, quartz, calcite and mica, or if you could just say that you observe both brittle and ductile deformation.

Finally, I personally do not think you need to say a combination of both, as I believe it is covered when saying that you observe brittle and ductile deformation. However, if you feel strongly about keeping that in that is fine.

Lines 265 – 268 – Similar to my comments above, the way that the first sentence here is written is a bit redundant as elastic and inelastic deformation covers everything. Again, I understand what you mean in that both occur, but then consider re-writing to something like "We observed that both elastic and inelastic deformation occurred during testing, and that both occurred simultaneously". You mention in line 268 that both occur simultaneously but have you got evidence for this?

Also could pore compression (line 266) not be inelastic rather than just elastic? Or do you consider inelastic pore compression as pore collapse?

Line 274 – Here you now use angle with respect to the maximum principle (presumably – but need to state this, as in engineering σ_1 is commonly the maximum principle tensile stress) compressive stress σ_1 in addition to angle from bedding and horizontal as before. I can understand why you may want to use σ_1/loading direction here as well, but then you should also indicate which fracture set these structures relate to (Fracture set 1?).

Line 284 – It is interesting that your microstructural analysis suggests that tensile cracks form as obliquely rather than vertically (parallel to the loading direction) orientated cracks. You do not mention this here but could this not be down to the transversely isotropic nature of the material, and that you load the sample oblique to bedding? Literature on the fracture toughness of shales at different angles to bedding suggest that during crack growth there is a competition for a tensile fracture to form parallel to load and parallel to the plane of weakness i.e. the short-transverse orientation. As a result, the actual fracture orientation lies somewhere between the two. Again, see the following:

Nejati, A. Aminzadeh, F. Amann, M.O. Saar, T. Driesner (2020) Mode I fracture growth in anisotropic rocks: Theory and experiment. Int J Solids Struct, 195 pp. 74-90, 10.1016/j.ijsolstr.2020.03.004

Forbes Inskip ND, Meredith PG, Chandler MR, Gudmundsson A (2018) Fracture properties of Nash Point shale as a function of orientation to bedding. J Geophys Res: Solid Earth. https ://doi. org/10.1029/2018J B0159 43

Chandler MR, Meredith PG, Brantut N, Crawford BR (2016) Fracture toughness anisotropy in shale. J Geophys Res: Solid Earth 121:1–24. https ://doi.org/10.1002/2015J B0127 56

Again, these studies are unconfined but I think that the formation of (apparent) tensile fractures in these studies may explain some of the observations that you have here with regards to the orientation of tensile cracks.

Line 292 – Should be "changed" not "changeed"

Line 320 – You use the British spelling of characterised here (with an s rather than a z) but use American spelling elsewhere (line 14, 84). Generally you use American spelling throughout, but be consistent.

347 – You use the term obliquely orientated here, but obliquely orientated to what, bedding, horizontal or σ_1? You use all three in the MS, and it may be that the cracks are oblique to all three, but you should state what the cracks are oblique to here.

Lines 351 – 352 – Here you state that there are few similarities with naturally deformed OPA. The manuscript and study are really interesting, however as you point out in your abstract important questions remain, particularly in relating data gathered in the lab to that observed in the subsurface. Your statement here suggests that you are not able to apply the results of your work to subsurface processes on a larger scale, which in my opinion undermines the great work that you have done. Although it may be true that your results do not corroborate well with naturally deformed OPA, you should expand on why you think this is, and how then your results are relevant. In the final lines of the MS you briefly suggest what could be done next, but you could expand on this to suggest how this study can better inform what types of experiments should be carried out next to tackle these open questions.

Line 521 - 522 – change "was conducted circumferential-displacement-controlled..." to "was conducted using a circumferential-displacement-control rate of 0.08 mm/min...".

Figure 3 right – The axis is labelled "angle" but what angle is this referring to? It is not made clear in the figure caption and given that the horizontal and the bedding direction are within 10° of each other it isn't immediately obvious which angle you are referring to. Please re label the axis "fracture angle to bedding/horizontal (as appropriate)"

Lines 536 – 537 – Here you just say "the oblique orientated fracture set" If you compare both fracture sets to the horizontal (which you do in line 537), they are both oblique i.e. not parallel or perpendicular to the horizontal. This also goes back to my previous comments of use one frame of reference only, bedding or horizontal, throughout. Bedding would be my preference.

Figure 4 – Is Figure 4 (b) an inset from Figure 4 (a)? If so indicate where it is from.

Also put a scale in Figures (c) and (d)

Figure 6 – Should the text in Figure 6 (a) be "Bent mica" rather than "Bend mica", this is also true for the figure caption and line 195 in the main text.

Line 565 – Here you reference (a, a', a") but only a and a' are shown in the figure. Also this may seem pedantic, but in the figure you use the prime symbol whereas you use the apostrophe in the figure caption, this should be consistent.

Figure 9 – I really like this figure, it explains nicely the features that you observe in your samples and describes the processes that have taken place. You also show an example of a saddle reef pore, but is there a 'real life' example that you could show in figure 7?