Solid Earth
Discussions

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Interactive comment on "Enhanced pore space analysis by use of μ-CT, MIP, NMR, and SIP" *by* Zeyu Zhang et al.

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Reviewers' Comments:

The submitted manuscript describes a study that aims to characterize pore size distributions, and the scaling of attributes, for two well-constrained types of sandstone using the following methods: 1) micro CT; 2) mercury intrusion porosimetry; 3) nuclear magnetic resonance; and 4) spectral induced polarization. Using curves of the cumulative volume fraction of pores and pore body radius, the methods are compared.

Generally speaking, the aims of the paper are clear, and data are well-presented. Improving our understanding of the nature of pore space in natural rocks is important to

a broad range of study areas, including petrophysics and rock mechanics, for which a comparison of methodologies will be potentially very useful. It is my view, however, that the manuscript, in its present form, contributes little to our understanding of natural pore variability; resolution cut-offs for these techniques have been discussed previously. Many of the sections need rewriting to avoid overlap and repetition, and the motivation, and context for the study are unclear. For these reasons, it has been a challenge to review as thoroughly as I would like. Some simple restructuring and clarification could improve this but additional work is also necessary. For instance, the authors state early on that they provide a "multiple length scale characterization of pore geometry" - where is this data? A sentence in the conclusion section refers to "μ-CT enables a geometrical description of individual pore space...", but no data are presented. Providing additional geometric data would greatly improve the novelty of the work, and appeal to a broader readership. If the authors lack this data, I recommend that they remove references to geometry throughout. Furthermore, there is virtually no review of existing geological (or other) data derived using the techniques, nor their application, and a scattered discussion of the results towards the end of the manuscript. This needs work before it can be considered for publication.

The authors may decide that additional data, and/or background and discussion is beyond the scope of this work. If this is the case, then considering the broad readership of Solid Earth, they might consider submitting the work to a more subject-specific journal.

As a final note, the manuscript should be given thorough proof-read from a native English speaker; language, grammar, and sentence structure require work before I think it is ready to publish. I have not made specific edits related to these because they are numerous. Below, I have provided section-specific comments for the authors. I hope the authors find them helpful.

MS Specific Comments

0. Abstract The abstract reads fine and, with some minor edits, reflects the main

findings of the manuscript.

Line(s) Comment 39 "...pore space geometry..." Global edit: you do not discuss pore geometry in this work. Please remove reference to it unless you have additional data to add.

1. Introduction This section needs some restructuring, and expansion. For submission to Solid Earth, the work should mention the existing applications of these methods (geological, and others). The authors could consider including a background section to present existing uses of each method, their limitations, and how this data is used. This would improve the framing of the work, and broaden its appeal to different readers. These are some questions I have from this section: a. What are your motives for the study? b. Who are you targeting with this work? Petrophysicists? Is Solid Earth the best place to present this? Porosity, and its effect on fluid flow and the mechanical behaviour of porous rocks is important to a range of study areas, and the subject of extensive study. A (brief) review of some the existing literature would help - e.g. recent uses of x-ray CT to analyse pore volume/geometry/distribution and fluid flow through porous media.

Line(s)

52-57 This isn't much of an introduction for the study. 63-67 I think you could move this to your discussion section and expand on how results from these studies compare to your own. 68-75 This section isn't very clear. You mention 3 separate published NMR studies but no others? It is not immediately clear what the relevance of these studies are to your own motivation, or results. You should add some background for the other methods too. Speaking for micro CT, there are several studies that analyse rock pores that the authors should take a look at, including: Lindquist et al., 2000; Ketcham, 2005; Nakashima and Kamiya, 2007; Takahashi el al., 2016; Schmitt et al., 2016; Saenger et al., 2016; Bubeck et al., 2017; Zhao et al., 2017 (this last one should be particularly helpful in helping you structure and present your work).

76-83 This section is partly repeated. Read through your introduction and keep it concise. 77 Either: add a section that deals with pore geometry specifically, and include additional figures/data, or remove this. 80 "...distributions are connected to each other..." This is unclear.

2. Methodology

This section is very long and it looks like a mixture of background and methodology, which could be split up. Keep your methodology simple: what did you do, and to what? A number of questions need to be addressed in this section to improve the clarity of your results. a. How many samples did you use in total? b. How many samples did you run for each test? This needs explanation to demonstrate that the results are repeatable. You could add this data to table 1. You should also explain what size samples need to be. c. Does sample size effect the results for any of the methods? It should certainly be considered in micro CT. d. Did you characterize grain size? What role will this play?

Line(s)

91-99 This is background 99 The use of fractals (in geology alone) stretches considerably beyond these references. If you are presenting data on pore scaling relationships, expand this and move to a background section. 100-102 Good. You should move your sample descriptions into this section. 103-108 Tell me what you're doing/using before you tell me the limitations of it. 109-110 How have you performed this analysis, what were the results, and why is it best? More information and figures to explain this process are needed. Why compare with 2D SEM images? 113 "... each individual pore..." Where are your data for individual pores? You could present data on the proportion of pore body radii (how variable are they within samples? How do your different sandstone types compare?), their geometry and preferred orientation (if present). 114 Do you have references for this technique? 119 You're using MIP specifically for pore throat radius? Be clear about what data each method is providing! 131-132 Try to

explain this more clearly. 139-145 Background. 142 "a capillary model with cylindrical pores, of uniform radius..." - How useful is this? Is it reasonable to assume a linear relationship for natural pores, which may be neither cylindrical, nor uniform? Kleinberg, 1996 applies it to "slit-like pores". You should provide some geometric description of your pore space to support the use of this model. At the VERY least, explain how your results could vary. You could leave this as is here, but add a section to your discussion covering possible limitations of the method and expand on this there. 150-151 "The range of resolved pore radii depends on the used value of surface reflexivity." - You need to explain what value you have chosen, and why? If similar assumptions apply to the use of a single value here, address it in the discussion also. 175 Quantify the "restricted range" 182 Did you have any repeatability issues? Do you think two sufficient? 187-224 This section is a mixture of background, discussion and results, with some repetition. Read through carefully and move elsewhere where appropriate.

3. Sample material This section is a mixture of methodology and results. Does it need to be a separate section? I think it would be helpful to have this information earlier. When you're describing the methods, it will help to know what they are related to. The section could also be much shorter. I recommend you edit the information into your methodology, explaining the number of samples used and their sample sizes

Line(s)

227-228 Cut this. Unnecessary. 244-245 Remove 245-247 Background 251-262 This is your data? It needs to be in the results section.

4. Results The description of the graphs in this section is rather vague and unhelpful - you refer to "differences" between curves but don't describe or quantify these. Equally, stating that something is "larger" or "smaller" is also unhelpful. Quantify your observations!

I suggest changing the section titles here to refer to the parameters measured, i.e. pore volume fraction, pore throat radius, and scaling. Describe the results of these for

each rock sample. This would be easier to follow than describing each rock; it is the technique that should be the focus of this section.

Your fractal data is currently lost in your discussion section. Move it into your results and consider a table that compares the dimensions obtained.

Line(s)

282 "...wide range of pore radii..." State the range measured for each method, with upper and lower limits clearly defined. 289 Explain this more clearly.

5. Discussion

This section is a confusing mixture of results and discussion. You should read through it carefully and remove results to earlier sections.

After reading the discussion, I have a number of questions that can be addressed by restructuring and expanding the discussion. a. What are the implications for the pore size distributions you have obtained? There is no real discussion of the importance of pore size distributions, or their use, in this work... b. What effect do you think your results have for studies of the mechanical behaviour and fluid flow properties of your samples? c. How do your results compare to existing characterisations of these samples - are you offering an improved resolution? How important is it for samples like this? d. How strongly dependent are your resolutions on rock type? How would they vary for other rock types: Limestones/volcanic rocks for example? e. Are the approaches described suitable for a range of rock types/sample sizes/porosities? I would like to see this section discuss the implications of the results more broadly. f. Which of the techniques is best? Which one provides the most, useful, information - and for whom? g. What are the limitations of your findings?

A summary table of the data provided by each method, and resolution would be helpful to readers. Also include a limitations section and use this as a basis to explain which methods should be used for certain applications, and how cautious researchers should

we be when interpreting the results.

6. Conclusions A lot of the material in this section could be moved into the discussion. Add a sentence summarising the importance of the result of this study.

Line(s) 399-407 These are (some of) your conclusions. The rest can be moved.

7. Figures/Tables

Suggested new figures: a. Demonstrate the 3D pore network would be helpful when describing your samples (e.g. Figure 3 in Zhao et al., 2017) b. Segmentation/MIS c. Plot your body radii against cumulative frequency.

Figure 1 No changes suggested. Figure 2 Label the two values (0.238 and 0.184) in the caption. Figure 3 No changes suggested. Figure 4 Label each part as A and B; describe them separately in the caption. Figure 5 No changes suggested. Figure 6 Label values as for figure 2. Figure 7 No changes suggested.

Table 1 Where does your permeability data come from? I recommend you convert these values to m2. Table 2 No changes suggested.

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