Review to the manuscript: se-2016-36

Manuscript title: X-Ray CT analyses, models and numerical simulations – a comparison with common analytical methods of an experimental CO_2 study.

Submitted by Steven Henkel, Dieter Pudlo, Frieder Enzmann, Viktor Reitenbach, Daniel Albrecht, Leonhard Ganzer and Reinhard Gaupp.

The manuscript intends a comparison of commonly applied analytical methods to characterize reservoir sandstones in terms of porosity and permability with the outcome of poro-perm determinations on 3D volume data derived from X-ray µ-CT analyses. A sound evaluation of prospects, limitations, and applicability of µ-CT-derived data to support the characterisation of reservoir rocks will be well within the scope of this Special Issue of SE.

However, in the current state the internal organization of the manuscript is not maximally optimized. The data space is quite diverse (1- analytical data on sandstone plugs used in this and also preceeding studies; 2- analytical data from plugs treated in autoclave experiments; 3- data from the literature replotted in this paper), and the assignment of the results to certain samples remains obscure.
In the conclusions, the analytical outcome of the µ-CT-derived poro-perm data is compared rather superficially, and not evaluated with great depth.

Certainly, a clarified and restructured manuscript in a state-of-the-art Special Issue of "Pore-scale tomography & imaging - applications, techniques and recommended practice" deserves to be more accentuated than a plain report of results of a collaborative research project. Please do communicate more of the enormous expertise and experience in terms of µ-CT that is gathered among the authors.

Recommendation: Major Revision.

General remarks:

1) Restructure the sample description and make the analytical results transparent by presentation of a table which lists each specimen.
In particular, please do clarify wether the measurements of He-porosity and N2-permeability were done on the same sample/an identical aliquot, and transparently connect the corresponding values (and not link to averages). This should be possible from the preparation of the µ-CT cubes and plugs that is described in detail in Henkel et al. (2014).

In the current manuscript version it is not easy to overview the samples actually used in this study:

- Fig. 2 lists the following samples: **seven** Tertiary, **eight** Triassic and **ten** Permian.
- the number of (*only Permian*) samples from the autoclave experiments it is neither mentioned in the sample section (page 5, line 11f) nor in the methods section (page 5, line 16f). The number of fluid samples is not mentioned (page 6, line 10); Tab. 2 refers **two** analyses. Does that mean, there are two Permian samples from the autoclave experiments? Are they included already in the data points in Fig 2, if yes, which ones are they?
- Fig. 5A and B list only **four** Permian, **four** Triassic and **two** Tertiary samples (even though problems where only mentioned for permeability calculations of the Tertiary samples), some Permian and Triassic samples from Fig. 2 are lost.
- *So is this actually the sample space that this comparison of µ-CT derived data with "classical" laboratory methods is based on?*
- Are Figs. 5. C and D are based also only on these **ten** samples, or is additional data included?
- page 9, line 12 informs about **sixteen** selected Permian sandstone plugs and **two** µ-CT cubes (other than the four from Fig. 5?). Please link transparently the results for µ-CT cube and the correlated plug, not just the average values for the plugs; **sixteen** Permian sandstones are definitely not depicted in Fig. 2. Please clarify
- Fig. 6B replots data of **sixteen** Permian samples of Pudlo et al. (2012). Are those the same that delivered the poroperm data reported on page 9, line 12 ff? Then please state in the text, and in the sample section

Could the authors be more precise about the locality of the samples in Fig. 1? It has been possible in the preceeding work of Henkel et al., (2013), where the three samples from Germany, also used in this study, have been documented already, and also in the study of Henkel et al., (2014), where all four samples are documented well concerning their location and concurrent reservoir conditons.

The dimensions of µ-CT cubes and the length of the plugs are mentioned only in the abstract, but not in the sample/methods sections. Please also state the plug diameter that was used for the He-Porosity and N2-Permeability measurements, which are to be compared to the µ-CT-derived poroperm entities from the 1cm cubes.

Is it really necessary to provide both almost identical Figs. 7 and 8, which report a volume reconstruction of one of the two µ-CT cubes before and after the autoclave experiment? A skillful move of both scale bar and colour legend would allow a presentation of the whole cubes that still would be higher magnified than currently in Fig. 8.

2) Determination of the (geometric) surface area by µ-CT is always an interesting topic that is worth some more remarks when drawing "conclusions". The numbers drawn from BET analyses inevitably differ from the results of µ-CT derived surface area determinations. The potential reader who seeks recommendations or is about to judge the applicability of µ-CT for surface area determinations on his samples might benefit from thoughts on the following aspects:

- BET does not only detect orders of magnitutes larger surfaces, it also is applied on crushed samples. Do samples develop cracks during this process that are identical to the (nano) pores the still aggregated sample? What about pore fillings and cementation?
- on the contrary, µ-CT is applied on an intact rock specimen, not disaggregated samples, and detects therefore only pores that are visible within the limited object resolution of the reconstruction. On what basis these values can be compared, and what is a good or bad result which can, or cannot, be in accordance with the classical method?
- are "micro"cracks of any relevance at all under the pressure conditions of the reservoir depth? As shown by measurements of the pressure dependence of ultrasonic sound velocities in reseroir sandstones (e. g., Fig. 10 in Gomez et al., 2010), those microcracks are a feature of the sample on the desktop and disappear in greater depth above ca. 40-60 MPa lithostatic pressure. Can BET under these circumstance regarded unambiguously as the "gold standard"?

3) As presented in the results section, amongst others an appropriate determination of porosity and permeability derived from from µ-CT scans is dependant on the resolution of the reconstructed images in respect to the fabric to be detected.

The authors quite simply conclude "very good accordance" for coarse and medium grain sizes (but they did not discuss the reason for the deviation of one Permian coarse/medium sand sample in Fig. 5A-B) and preclude the persistence of the "*minimized accordance*" (which refers to the failure of connected porosity in some Tertiary samples that hinder flow simulations) in the future.

Does only the grain size matter, and not also form factor, cementation or the occurrence of pore fillings, which certainly affect the existence of resolvable pore space?
Here, the outcome of the permeability simulations is presented as ground truth, without an evaluation of its correctness (only two references are given, and one is the vendor's software tutorial).
Has it been likewise successful to process permeability data through the fabrics shown in Fig. 3 A-C, which do not differ much in grain size (if crushed, 3A might actually exhibit smaller grains than 3C) but in the occurrence of pore fillings/cementation?

What do we learn from the presentation of the different lithotypes in Fig. 4? Has this been introduced into an evaluation or recommendation?

Please provide a slightly more profound discussion and conclusion in this respect.

Detailed remarks:

- Abstract, line 15: provide also information about the plug diameter, and include the information regarding plug size and cube size also in the methods section
- abstract, line 25: please rephrase "even regarding only CT-single scan of the rock samples". What exactly is meant by this phrase?
- page 2, line 2: provide a translation or rather an explanation of the term "Energiewende"
- page 3, line 7: strenghened
- page 4, line 2: ...rock fragment content of the different locations...
- page 4, Fig. 2: If printed b/w, the grey value of Permian and teriary samples are very similar. Could you use differing symbol shapes (instead of circles only) or lighter colour for Tertiary
- page 5, line 8, caption Fig. 3: there are no arrows present in Fig. 3C
- page 5, line 9: ...in conducting this study: please rephrase
- page 5, line 10+line 12: Fig 5 is referred to earlier in the text as Fig. 4. Please rearrange order of figures or text
- Page 5, line 11f: please state already here that only the Permian samples were used for autoclave experiments
- page 7, line 23/25: which sense does a mean permeability value have
- page 8, lines 2-4, and page 9, lines 17/18: there seems to be a formatting problem: the exponent ^{2} is missing in the m^2/g and cm^2 units
- page 8, line 1: of what predictivity is the specific surface area of crushed rock fragments, when it is compared to the geometric rock surface of the pore space, as detected by µ-CT (with the limited resolution of ca. 8 µm per voxel)
- page 8, Fig 5: please significantly increase the text size of units and descriptions of the axes
- page 9, lines 17/18: It is unclear, why cm^2 is presented as a unit for surface measure: (1) If it is also specific surface area, the cm^2/g is missing in the unit. In this case the authors should specify, how rock density was calculated or estimated to provide the relation to mass; (2) if it is just a surface value, the authors should at least state the corresponding sample volume and

provide a clue, on what basis these values are compared to the specific surface area values yielded by the BET method

- page 10, Fig 6: please significantly increase the text size of units and descriptions of the axes
- page 12, line 1: mind punctuation "... , using ... experiment, ..."
- page 14, line 6: modified

Reference:

Gomez, C. T., Dvorkin, J., and Vanorio, T. (2010). Laboratory measurements of porosity, permeability, resistivity, and velocity on Fontainebleau sandstones. GEOPHYSICS, 75(6), E191-E204. doi: 10.1190/1.3493633.

For convenience follow: http://library.seg.org/doi/pdf/10.1190/1.3493633