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Interactive comment on "Evaluating porosity estimates for sandstones based on X-ray micro-tomographic images" *by* Mathias Nehler et al.

Edward Andò (Referee)

edward.ando@3sr-grenoble.fr

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I think this paper presents a careful study of the measurement of porosity in sandstones – a measurement of primary importance for the mechanical behaviour and permeability. The paper is essentially what I wold consider a technical note, so most of my comments are technical. The paper is interesting to publish but it has some flaws. In order of importance:

1. The take away message is quite specific and quite difficult to digest. This is, in my opinion related to the lack of theoretical results regarding porosity measurement which could both render conclusions more general, but also make the

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paper more appealing. An example of what I'm saying is to study the effect of signal-to-noise, blurring and pore size on the error of porosity estimation on a synthetic test case with only two phases. This could easily be done by clipping correctly-calculated partial volume spheres representing pores out of a block of material (what mathematical morphologists call a meatball geometry). This will allow some expectations of how these three key parameters affect the measurement, allowing your real measurements to be put into context, and yielding useful relations about blur vs pore size for accurate porosity measurements for example. Furthermore filtering can be tested synthetically.

2. Some strange choices have been made on treatment of the x-ray tomography volumes. First of all there are some clear artefacts in the high-resolution images that are not really commented. I'm afraid that Median and NLM are really odd choices – median filtering is really only used by professional for removing extreme values, and NLM is so non-linear that it's behaviour is difficult to characterise. It's surprising that grey-mass preserving filter such as averaging (and without thinking about it too hard Gaussian blurring should also be) would be more suitable. For more advanced filtering Bilateral filtering as discussed abundantly in the literature from the Canberra group is a much better choice since it is local. A number of parameters are missing (structuring element for filters?). Another key point is that a very strange choice has been made to study thresholded images. If you believe that the partial volume effect holds, and that greylevels are a linear function of voxel occupancy (reasonable) for a two-phase material you can calibrate the greylevel of pores and solids and assign a porosity to each voxel with an interpolation. This calibration will remove the thresholding step and should return much less noisy images. Again this can be proved on a synthetic example as suggested above.

3. A number of laboratory measurements have been made. This is really good to compare to the x-ray measurements, however the different measurements do not seems to be consistent between each other (different non-tomography tech-

niques do not fall into the error band of each other). This key point needs to be analysed and discussed further... different ways of measuring the same thing must yield values within error, otherwise the same thing is not being measured (or errors are underestimated).

Furthermore, I am not exactly in this field, so perhaps habit are different, but I find in a number of places that overly general and not supported by facts that are presented. Some of the language surrounding x-ray acquisition and reconsrtuction is a little bit inexact, and I have offered some comments to improve this.

Comment before starting to read this paper: judging from the layout in the abtract, I would like to make the following predictions, that we could take as a reasonably expert's guess:

- Otsu is best
- No filtering is best (unless gaussian blur is used). To quote J.C. Santamarina "The best amount of filtering is none"
- pores smaller than 5*pixel size are a problem

Synchrotrons do not generally produce monochromatic beams (wigglers and bending magnets don't in any case...), but generate enough flux that the beam can be monochromatised while keeping good performance.

There is normally a negative sign in the exponent, unless your μ values are negative. It may be worth talking about the dependence of μ on x-ray energy, which will allow beam hardening to be introduced with more ease later.

Artifacts? Artefacts.

"This non-uniqueness".

What is non unique? I propose to say "this spatial averaging process"

> "...results in a blurring of all phase boundaries in a CT image."

This is not blurring, it is the manifestation of the discretisation of the measurement. I agree that boundaries of phases will be filled with partial volume voxels, but this is an expected result of voxel-volume averaging.

This sentence is not homogeneous:

> "The spatial resolution of the tomographic image produced by conventional X-ray CT is limited by the diameter of the X-ray source, the X-ray photon energy, the absorption of the sample as well as the number and size of pixels on the detector"

> "However, the (isotropic) voxel size is the calculated size of a discrete cubic volume element in the reconstructed image, which can actually be lower than the actual spatial resolution of the image"

Sure, but it's a pity to cop out of measuring at least the radiograph resolution with standard techniques.

In my experience, off focal radiation is a detail compared to mechanical stability of imaging system. Maybe also with noting phase contrast effects?

> "Standard CT systems do not record voxel intensities in terms of any physical unit but rather map the data to a somewhat arbitrary range meeting either the data storage requirements (e.g. 0 to 65535 for common 16-bit integer dataformats) or, to ensure compatibility of images from different CT systems, transforming the data to so-called Hounsfield units or CT numbers." ...and later... "Due to the non-physical units of the image data"

Weeell, no, I don't really agree. Non-physical units means that they are units what make no physical sense (to me). Here the units of the reconstructed image are a complex energy-integrated attenuation coefficient which you cannot express the units for, but this does not mean they do not exist. 16-bit integers are only used as output formats, all reconstruction codes are at least float internally for numerical reasons, so "record voxel intensities" is also wrong. Furthermore, a detector records, here we are reconstructing, computing, calculating, inverting but not recording.

Aesthetic comment: please don't abbreviate sandstone to sst, why? to save 5 characters? It decreases readability for no reason.

Rabbani is an odd reference for the watershed...

Reconstruction process is back projection? "Convolution and back filter" is really not clear.

> "...mapped to a 16-bit integer range between zero, corresponding to the background, in our case air, and 65535, corresponding to the detection limits of the CT-Scanner..."

For quantitative studies (this like one is aiming to be) cutting the reconstructed values at zero (zero what?) is bad practice, since you miss the noise distribution below zero for the background. Re-reading the sentence, I'm afraid to say that it's all meangingless and should be re-written – zero is not defined, and the "detection limits of the CT-Scanner" are not well defined (with a lump of lead what are your detection limits?).

After citing so much work by Sheppard I'm sad to see that you are not going to try a Bilateral filter which is a clear and well-defined local filter compated to the complex and hard-to-characterise NLM filter.

Details of NLM filter setting please.

GBS points counting way off, probably copy-paste error with below, PLEASE CHECK!

Comment on the fact that all measurements of porosity in Table 2 with their associated errors rarely fall in the same margins! This is a clear indication that the errors are extremely underestimated, or that these porosity measurements are in fact measuring different things. I'm sorry if this is a trivial point, but it's still very surprising. I would really like an answer to this point.

> "Images obtained using X-rays pre-hardened by filters have a higher signal to noise ratio than those taken without a filter..."

Why such a general sentence so far in the document? This is not true in many cases, like in biological samples.

> "absolute voxel intensities are displayed using a uniform gray value range"

This is a bit rich considering you've said that they are non-physical... See comment above.

> "The quality of images taken with a focal spot diameter of 1 μm and without X-ray filters (Figure 6, FS9) is similar to images recorded with a focal spot diameter of 5 μm using aluminum filters (Figure 6, FS8)."

This is nonsense, remove it. Blur and contrast are two independent axes of image quality – which may be coupled in your system, sure, but you really should not feel empowered to make this kind of general statement, it's utterly undefendable.

Figure 6, there is a fair amount of geometrical inaccuracy in the reconstructions with small pixel sizes, which looks like motion blur, which should be mentioned (FS9, WS, OS, FS8), could this be a cause of skewness?

Non-local means example (c, g) in Figure 7 does not fill me with joy, it's a very strange result of filter, with some edges sharpened and some texture remaining in the grains. This is the fundamental problem with NLM, that filtering is not homogeneous or isotropic, and there is little control of how and where the algorithm chooses to filter. I've extracted the original image from the PDF, and run 20 iterations of Bilateral, which denoises nicely – if I can upload them with my review I will. The blurred edges due to motion blur seem to be interpreted in a strange way by the filter.

Figure 8 shows a very dramatic change of the automatic thresholds. In some cases the second peak is very hard to see – adding the log of the pixel count (which is quite typical) would help in this regard.

> "In general, the difference between lab and CT porosity increases with increasing sample size and decreasing porosity."

This is pretty much expected since you are using a thresholding approach. On page 15 line 10, I think a more theoretical discussion about grey-scale-preservation in filtering (not guaranteed by either of the filters used, unlike an average filter) will help make the discussion more precise.

> "We therefore conclude that filtering generally does not improve porosity determination."

Woah there, the choice of two strange filters does not allow such a general conclusion!!

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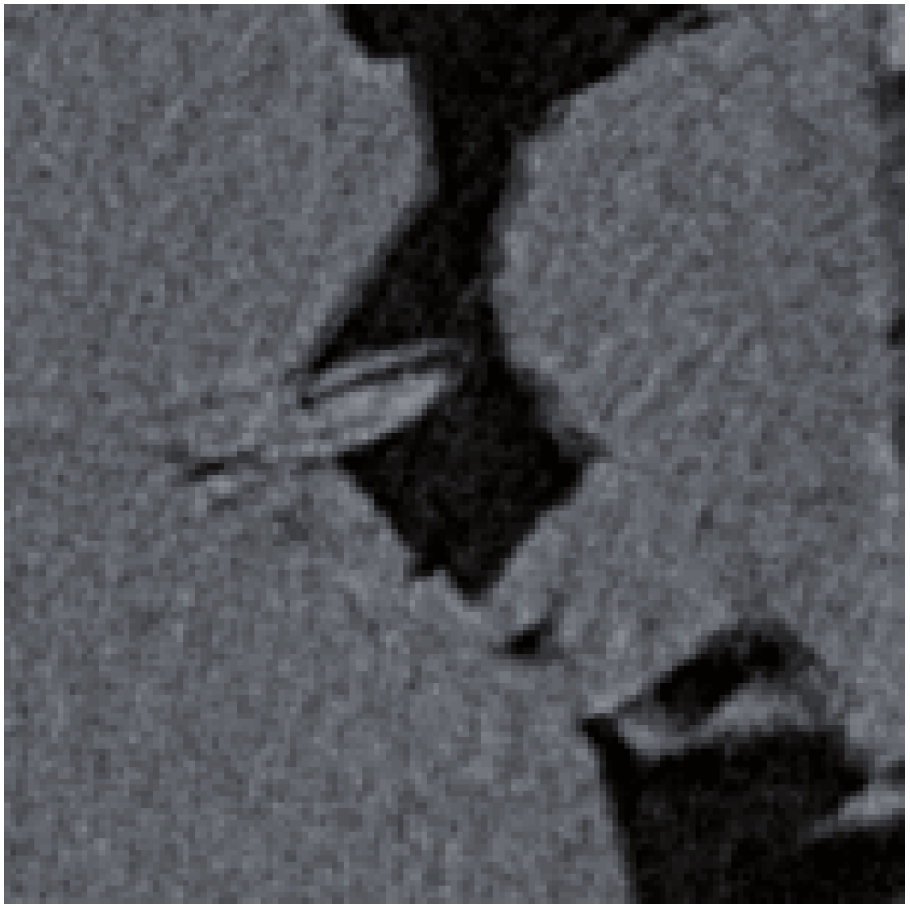

Fig. 1.

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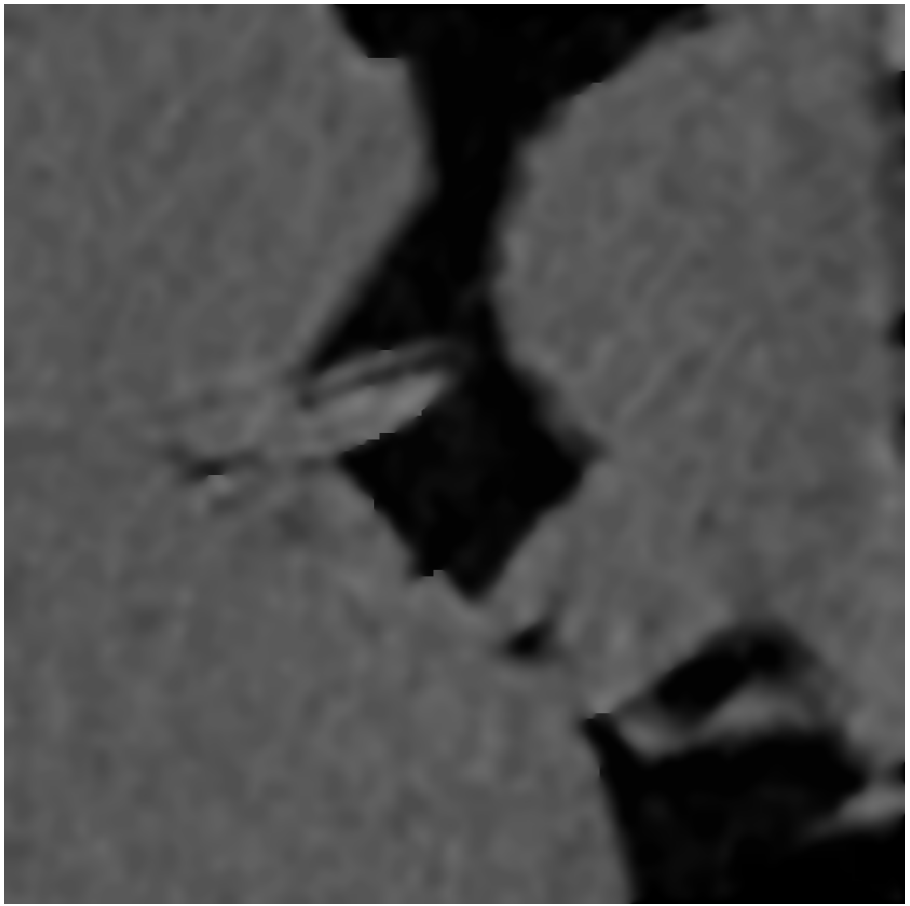

Fig. 2.