

Response to the Reviewer #2:

We thank the reviewer for handling our manuscript. Response to the specific comments is presented below:

General Comments

This paper has made commendable efforts to using a multi-scale, multi-methodological approach for the petrophysical characterization of reservoir sandstones. The strength of the study lies in its multiple datasets generated and used. However, the paper requires improvements before it can be ready for publication.

1.Comment:

*The main aims/objectives of this study should be made very clear from the start. Are you proposing **multi-methodological approach** for the petrophysical characterization of reservoir sandstones as the best or only **method**? Or what exactly are you aiming for?*

Response:

The objective of the paper is formulated in lines 68-69 in the introduction:

“The present paper provides a detailed description and evaluation of a **multi-methodological** petrophysical approach for the comprehensive multiscale characterization of reservoir sandstones.”

The word “**method**” questioned by the reviewer appears in lines 62 and 73 in the introduction in the following context:

Line 62: “Over the past few decades, pore-scale imaging and flow simulations (citations...) have started to serve as a reliable **method** for rock characterization.”

Line 73: “The suggested computational workflow enables the identification of Darcy-scale permeability links to an extensive set of geometrical, textural and topological rock descriptors, quantified at the pore scale by deterministic and probabilistic (statistical) **methods**.”

These **methods** are the parts of **the multi-methodological approach**, which is specified in lines 69-71 in the Introduction: “The proposed **approach** includes petrography, gas porosimetry and permeametry, mercury intrusion porosimetry, 3D imaging and several kinds of pore-scale modelling.”

2.Comment:

How the achievement of these aims/objectives contribute to the current knowledge gaps should be clearly discussed in the relevant section of the paper.

Response:

This contribution of the objectives questioned above is presented in detail in the last paragraph of the introduction (lines 76-82):

“The approach presented herein is especially important for the detection of anisotropy and the identification of its origin at various rock scales. The multi-methodological validation procedure is significant for properly upscaling permeability from the micro scale to the macro scale (Ringrose and Bentley, 2015). This validation, thereby, allows an accurate petrophysical analysis of reservoir sandstones with broad ranges of textural and topological

characteristics. The findings contribute also to the current geological knowledge regarding non-marine sandstones of Lower Cretaceous age (e.g., Akinlotan, 2017; Li et al., 2016; Ferreira et al., 2016) and specifically regarding the studied stratigraphic unit.”

Some aspects contributing to the current knowledge on anisotropy and on its impact on the clastic formations, will be extended and several more references in this and other context, will be added in the revised version.

3.Comment:

The methods need to be clearly discussed.

Response: Pls see our response to the comments #11 and #13 below.

4.Comment: *Many figures require attention.*

Response: The quality of all figures will be improved in the revised version of the paper.

5.Comment

I do feel that testing all the proposed conclusions made from this study with sandstones from other places will make these conclusions stronger. If it is possible to have sandstones from other places to test your conclusions, this will be very good. However, if the aims/objectives of the study do not require/permit this, then no problem.

Response:

We do not have the “Darcy-scale permeability links to an extensive set of geometrical, textural and topological rock descriptors, quantified at the pore scale” (from our objective) derived for other sandstones, to perform a valid comparison. So that the general comparison of one sandstone to another one will just move our paper to the category of the regional studies, which should be avoided. Besides, sandstones feature a big complexity and variability, which seems to be impossible to address properly in this paper.

Specific Comments

6.Comment:

Title

Why is there ‘benchmark’ in the title? Depending on the revised aims/objectives of the study, the title may require revision.

Response:

The title could be changed to “Validation of a multi-scale, multi-methodological approach for the petrophysical characterization of reservoir sandstones”.

However, because benchmarking is comparing results or processes with the “reference” data or processes, and this is exactly what we perform in the paper for the upscaling task, the change of the title would finally depend on the on our implementation of the comment #8 of Reviewer #1. Eventually, if we will add the results from the additional permeability simulations on other REV size geometries of sample S3, then this would underline the benchmarking of the study even better than before. In this case the title will stay as previously.

7.Comment:

Introduction

An extended literature review is required. This may be part of the introduction or may be a separate section. This is important to discuss the state of the subject matter and to present a framework and context for which current study fits into. The current introduction is short while the aim of this study does not seem to address some of the issues raised (lines 66-67) in previous studies.

Response: We will extend the introduction, keeping the framework of validation of the multi-methodological study and upscaling.

8.Comment:

Geological Setting

Abbreviation in line 98 needs to be written in full at first time.

Response: Fe-ox will be changed to “Fe oxide (Fe-ox)” at the first occurrence

9.Comment:

Fig. 1 needs to be increased in size to make it legible. The quality of 1d needs to be improved. 1a needs lines of latitude and longitude.

Response: These changes will be implemented

10.Comment:

Appendix A. It is a bit strange that important geological information is put in an appendix. The key geological information in the appendix needs to be summarized and placed under geological setting. The information presented in this section is too shallow and only focused on a formation. Every relevant geological information about the whole basin and other formations should be included here to give a very good context for the current study.

Response: Moving the geological information to the appendix was requested by the former editor for refocusing this manuscript to its current scope. Information currently provided by Appendix A will be summarised and placed under the geological settings in the revised version. However, the scope of the geological information will not be extended to other formations, to agree with the aim and the scope of the current refocused manuscript, which does not present the regional study (as it was previously) but rather a validation of the multi-methodological approach.

11.Comment:

Methods

3.1. How many samples were collected? Is it possible to state the size of these samples and large block samples or show their photos so that readers can have an idea of how big/small they are. There needs to be proper descriptions of all these samples: how can

a reader identify/differentiate a sample from large block samples and from a sub-sample?

Response: The reviewer is invited to look at lines 119-124 at the manuscript where the information about the number of samples is presented:

“Large sample blocks were collected from these three layers, and the directions perpendicular to the bedding planes (defined as the z-directions in our study) were noted. Subsequently, in the laboratory, smaller sub-samples (**described below**) were prepared from these large samples for textural observations and various analytical measurements and computations. In total, 7 sub-samples from the top layer, 8 sub-samples from the middle layer and 4 sub-samples from the bottom layer were investigated in the laboratory (Table 2).” The information about the number of samples for each test is also indicated in Table 2 and also below Table 2 in the legend.

With respect to the sample sizes: The reviewer is correct, the approximate size of the largest blocks (10÷20 cm) retrieved from the rock at the outcrop is not specified in the manuscript, it will be inserted in the revised version. However, all sample sizes and their shapes used for the specific measurements are specified in the manuscript:

Lines 129-131: “Specimens ~5-7 cm in size were investigated by petrographic and petrophysical lab methods. Sub-samples ~1 cm in size were retrieved from the aforementioned plugs for investigation by 3D imaging, digital image analysis and simulation techniques (described in more detail below).”

The sizes were repeated further in the manuscript at the descriptions of the specific measurements:

Lines 142-143: “Effective porosity and permeability were evaluated on dried cylindrical samples (2.5 cm in diameter and 5-7 cm in length)”

Lines 147-148: “Mercury intrusion porosimetry (...) was applied to dried cylindrical samples ~1 cm³ in size”

Lines 169-170: “cylindrical subsamples 4-8 mm in diameter and 5-10 mm in length were retrieved from the larger samples studied in the laboratory and were scanned...”

With respect to the photos suggested by the Reviewer: because of the big difference in the samples sizes (specified above) and because their dimensions are clearly and repeatedly specified in the paper, we will not insert their photos into the revised version of the manuscript.

12.Comment:

Table 1. 3.7 should be ‘Optical microscopy’

Response: Table 1, point 7 “Petrographic microscopy” will be changed to “Optical microscopy”

13.Comment:

3.2 The laboratory methods are not properly discussed and this is not good enough. More than just mentioning the names of equipment used, the procedure needs to be properly discussed or appropriate references provided.

Response: Methods 1-7 specified in Table 1 are the “classical” ones with well-established protocols available elsewhere. We will add a brief introduction to the Methods section and specify more references, in order to point this out more precisely.

14.Comment:

If the methods are properly discussed, I do not see any need for Table 1. Only the relevant information needed to understand the procedure for the workflow method should be provided. The current format appears to be excessive.

Response: Extended computational workflow (number 8 in Table 1, Fig.2) is one of the main methodologies of our study. It combines a number of methods with some variability in their application which is not obvious (e.g., especially with respect to the filtering, segmentation, and REV estimation). Despite this, some of these methods (Fig.2a-2c) are described in the text in very brief, e.g. see lines 165-185. REV estimation demands an especial attention in the current paper due to its importance for the anisotropy estimation (see lines 191-215 and comment #2 of Reviewer 1). Flow modelling could also be applied in several ways, with respect e.g. to the boundary conditions and to the averaging procedures. However, those are currently described in brief as well (lines 216-237). Some text from the image analysis (specified in lines 238-257) will be moved into the appendix in the revised version, following the reviewer suggestion.

Table 1 summarizes methods and petrophysical characteristics determined from the these methods (similarly to Table 1 in Tatomir et al. (2016) focusing on the similar rock). This allows an immediate comparison between the output of the corresponding methods. This will be clarified in the text and in the legend to the Table 1.

15.Comment:

Results Line 269, 314, -what heavy minerals?

Response: “heavy minerals” will be replaced with “Fe/Fe-ox bearing minerals”

16.Comment:

268, 270: referencing methods using ‘according to’, ‘following’ should be amended using journal style

Response: This paper was edited by the professional AJE editorial agency (certificate # 13B3-B361-ED59-44F5-4FB0, attached to this response) in accordance with SE journal style.

17.Comment:

276; Mn-Ox: what is this? Please explain?

Response: Mn-ox is the manganese oxide, which will be clarified in the text in the same way as for Fe-ox before (your comment #8).

18.Comment:

317-include reference

Response: An appropriate reference with a classification of the “quartz wacke sandstone” (Pettijohn et al., 1987) will be included.

19.Comment:

318: result is mixed with interpretation. Only the results should be presented in the result section in this place and throughout the manuscript.

Response: The sentence “The pore network is influenced by the extent of clay deposition on coarser grains, identified mostly in laminae (Fig. 4a, d).” will be substituted by “The pore space is reduced by clays deposited on coarser grains, identified mostly in laminae (Fig. 4a, d)”

20.Comment:

Fig 4d-scale is missing

Response: The scale will be added in the revised version

21.Comment:

347-349 should be moved to the methods section

Response:

To agree with the corresponding descriptions of the top and intermediate unit layers in the Results section:

“**Sandstone S1:** The top unit layer with a thickness of ~1.5 m (Fig. 1c) consists of yellow-brown sandstone (Fig. 3a), which is moderately consolidated ...” (lines 267-268)

“**Sandstone S2:** The intermediate unit layer with a thickness of ~20 cm consists of grey-green moderately consolidated sandstone (Figs. 1c, 4) ...” (lines 310-311),

the following sentence for the bottom unit layer, addressed by the reviewer:

“**Sandstone S3:** Samples were taken from the ~1.5 m thick bottom unit layer in the outcrop (Fig. 1c) consisting of (pale) red-purple poorly consolidated sandstone with grains covered by a secondary red patina (Fig. 5).” (lines 347-349)

will be changed to:

“The bottom unit layer with a thickness of ~1.5 m consists of (pale) red-purple poorly consolidated sandstone (Fig. 1c) with grains covered by a secondary red patina (Fig. 5).”

22.Comment:

Fig 6 and 7, 9, 11, 12 should be increased

Response: The quality of these figures will be improved in the revised version of the manuscript

23.Comment:

480-485: more or less a repetition. Any new information here should be moved to methods section. The results of the modelling should be presented here.

Response: The questioned text from lines 480-483 is presented below:

“Fluid flow was modelled at the pore scale in two different micro-CT-scanned geometries: 1) a full cube of sample S1, including two adjacent parts possessing relatively low (0-250 voxels) and high (250-1180 voxels) porosities (Fig. 9c), and 2) sample S3 within its REV dimensions (Table 3). Modelling of the 3D geometry of sample S2 was not performed due to the reasons detailed above.”

This text from the first paragraph of the subsection 4.3 on Flow modelling can not be moved to the Methods section as it relies on the results of the REV analysis presented in the preceding subsection 4.2 of the Results. The following sentence “A constant pressure gradient of 2.424 [Pa / mm] between the inlet and outlet boundaries was applied in all the simulations for consistency.” will be moved to the Methods to the description of the flow modelling.

24.Comment:

509-511: needs to be in the methods section

Response: The questioned text from lines 509-511 is presented below: “For S1, the mode peak of the pore size distribution (measured by a Feret maximum calliper) (Fig. 13, red line) is at 194 μm (Table 2). In total, 3500 pores were analysed. The pore specific surface area (PSA) calculated from micro-CT images is 0.068 μm^{-1} .”

The knowledge presented in these sentences, including a number of the analyzed pores, is the direct result of the application of the image analysis (see lines 239-241 in Methods section). These are not known before running the model of the image analysis. Hence, they should stay in the Results section.

25.Comment:

513-514: is this result or interpretation?

Response:

“The tortuosity, measured from the whole CT image, indicates similar values in the x- and y-directions of 1.37 and 1.38, respectively, whereas in the z-direction, the tortuosity is 1.48 (Table 2). As many paths were considered, we suggest that this difference is created by the textural features that appear in horizontal planes (Fig. 3a).”

Both sentences include the results of the conducted image analysis indicating an anisotropy. We will change the second sentence to “As many paths were considered, this difference is an indication of the textural features that appear in horizontal planes (Fig. 3a).”

26.Comment:

545: if the information in appendix C is important for the discussion, why is it not included in the main body of the manuscript?

Response:

Appendix C presents the definition of the Euler characteristic available elsewhere and used in the image analysis. It was excluded from the main text in order to reduce the amount of

text related to the image analysis in the Methods section (lines 238-258) (see our response to reviewer's comment #14 above). Because these two requests contradict each other, we decided to leave this text in the Appendix C and thus to shorten the Methods section. In addition, there is also no need to insert this "basic" definition to the Discussion. Therefore, it will be just referenced, as below.

"The value of the connectivity index of S3 (10) is approximately three times higher than that of S1 (3.49), while both rocks are defined as moderately sorted sandstones (Table 2). This difference is due to S1 having a smaller number of inequivalent loops within the pore network than S3 (**Appendix C**), leading to smaller β_1 values in Euler characteristics"

27.Comment:

560: *gravity-dominated?, capillary-dominated?*

Response: SE English guidelines do not allow using hyphens in the specified grammar context: https://www.solid-earth.net/for_authors/manuscript_preparation.html

28.Comment:

601: *use 'study' instead of paper, here and throughout the manuscript*

Response: Will be changed throughout the text where applicable

29.Comment:

603: *'very heterogeneous in nature'?*

Response: Will be changed

30.Comment:

References

I have not bothered to check the references at this stage. The author needs to ensure that all cited references are in the bibliography and vice. For example, I am not sure if I encountered Akinlotan 2018 in the text but it is in the bibliography. Please look into this and others and ensure referencing is accurate.

Response: The list of the reference will be verified and adjusted accordingly in the revised version of the manuscript.

References

Pettijohn F. J., P.E. Potter and R. Siever, 1987, *Sand and sandstone*, 2nd ed. Springer-Verlag. ISBN 0-387-96350-2.