**Introduction**

Pore microstructure has been considered to have significant effect on flow capacity, storage capability and recovery efficiency. Parameters, including pore size, geometry and connectivity are quantified to characterize pore network of tight reservoir, which can be obtained by using direct and indirect techniques, such as thin section, MICP, NMR, SEM, and X-ray computed tomography (micro CT). The pore network of tight reservoirs is featured by complex structure, poor connectivity, and high heterogeneity, and thus the dimension of pore network and the representative of core sample should be considered when choosing the analytical techniques.

X-ray computed tomography, as a non-destructive technique, has been applied in visualization and quantification of internal structure of objects in geosciences since the 1980s (Cnudde and Boone, 2013; Conroy and Vannier, 1984; Long et al., 2009) (Fransham and Jelen, 1987). The improvement in the resolution of computed tomography promotes the further application in the quantification of mineral spatial distribution, petrophysical property and pore microstructure (Remeysen and Swennen, 2008; Van Geet et al., 2001). As a rule of thumb, X-ray CT gives more information in three dimension and the length scale ranges from nanometer to centimeter, when compared with other analytical techniques (e.g., SEM, MICP). X-ray CT presents finer and detailed visualization of pore network, which gives insight into the nature of pore network (Zhang et al., 2019).

Furthermore, pore network can be established by centerline tree algorithm and pore network model (PNM) algorithm, which are often used in the digital core analysis. The centerline tree algorithm preserves the basic topological features in and removes most of the unnecessary information of pore structure, while pore network model extracts the skeleton network and balls and sticks are used to represent pore bodies and pore-throats respectively. Single phase and multiple phases flow simulations present the displacement process, which visualize the preferential pathways of fluid flow and velocity and pressure distribution.

Herein, pore microstructure of tight reservoirs was characterized using high-resolution micro CT data and corresponding flow transport properties were predicted using pore network model algorithm. Samples from the Lucaogou Formation of the Jimsar Sag, Junggar Basin in the northwestern China were selected for micro CT scanning, where representative elementary volume (REV) and image resolution were taken into consideration. Pore geometric and topological features of REV were quantified and numerical simulations were conducted, aiming to determine the effective transport capacity of the selected samples.

**Methods**

Cylindrical samples with a diameter of 2 mm were drilled and glued on a carbon fiber, which was fixed by a metal holder. And then the holder was mounted onto the lifting platform to guarantee that the sample was located between the X-ray source and the detector of micro CT (Xradia Versa 510). The X-ray accelerating voltage was chosen as 60 kV and the objective lens was selected as 4 X, achieving a voxel size of $(0.75 \mu m)^3$. A series of 2000 radiographic projections were recorded by the detector and these two-dimensional projections were subsequently reconstructed by XMController software developed by Zeiss.

The reconstructed three-dimensional images were analyzed using Avizo software, including noise reduction, pore segmentation, and permeability calculation. Micro CT images were filtered using non-local means filter algorithm and then pore phase was segmented using watershed algorithm.

Multiple concentric cubic volumes with various length scale were analyzed for the REV determination of tight rocks, where porosity and specific surface area were used as criteria to validate the size of REV. Besides, quantitative parameters of pore and throat for REV, such as volume, surface area, and equivalent diameter, were obtained by the label analysis of Avizo. The bulk properties (e.g., porosity and permeability) were calculated and compared with the helium gas porosity and permeability of
samples, which were measured by the HPP porometer (produced by Corelab) following SY/5336-2006 standard.

**Results and discussions**

Variations of porosity and specific surface area (i.e., the ratio of surface area to volume) vanished gradually with the volume increase of field of view. Note that the size of REV determined by specific surface area was commonly smaller than that indicated by porosity, which fluctuated among different samples. The size of REV ranged from $(200 \, \mu m)^3$ to $(500 \, \mu m)^3$, the heterogeneity of pore microstructure was of significant importance to influence the bulk properties of tight reservoirs (Figure 1). The porosities of REV obtained by micro-CT images distributed in a range of 3.8 % - 12.5 %, but they were commonly less than those obtained by helium porometer. This was mainly attributed to the relatively low image resolution, where nano-scale pores were unable to be distinguished during the segmentation.

<table>
<thead>
<tr>
<th>Sample NO.</th>
<th>2D slice</th>
<th>2D pore</th>
<th>3D pore</th>
<th>Pore skeleton</th>
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<tr>
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<td>2-7</td>
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*Figure 1* Pore microstructure characteristics of tight rocks analyzed by micro-CT data. Two dimensional original image, the segmented pores in the two dimensional images, three dimensional volume rendering of labelled pores and the skeleton model of pore network were shown for each sample, respectively.

Pores were identified to be mainly associated with minerals, including feldspar, quartz, dolomite and calcite. Part of the primary pores were reworked by dissolution and cementation, which were proved
by the high-resolution SEM image analysis. The dissolution diagenesis was crucial for forming large pores in the fine-grained sedimentary rocks, and these pores presented complex shapes. Pore shape was quantitatively analyzed by shape factor defined as $6\sqrt[3]{\pi V/S}$, where $V$ was the pore volume and $S$ was the pore surface area. Shape factor showed a negative correlation with pore size, indicating that the larger pores commonly had irregular and curved morphology.

Pore size distribution showed a similar pattern and the majority of pores were less than 10 μm, whereas differences in volume contribution of pores were shown in the Figure 2. Besides, pore volume followed a power law distribution, where a larger exponent $\tau$ indicated the pore network was dominated by smaller pores. Notably, sample 2-3 presented the largest $\tau$ ($\tau = 2.32$) and pores smaller than 10 μm contributed significantly to the total pore volume of tight rock. Pore volume distribution changed from bimodality to unimodality with the decrease of exponent $\tau$ (Figure 2 and Figure 3A), which suggested an increase of contribution to the total pore volume. Apparently, exponent $\tau$ was only relevant to the pore size rather than the heterogeneity of pore spatial distribution, as suggested by Figure 1. Thus, pore density was calculated to investigate the heterogeneity of pore network, which was of significant importance for controlling the flow transport capability. As suggested by Figure 3B, pore density of sample 1-2 distributed over a relatively large range, indicating higher heterogeneity than other selected samples. This results were in accordance with the skeleton frame analysis of pore network (Figure 1).

Transport capability of tight rock is significantly controlled by the pore structure, especially by the structure of connected pore network. The skeleton presentation of pore network, removing redundant information of the pore system, provided necessary numeric parameters for the prediction of transport properties. Tight reservoirs presented significant differences in their flow potential and storage capability. High transport capability was related to the most conductive pathway, which was associated with the larger connected pores (e.g., sample 2-7) as shown in the Figure 1. These pores were the dominant space for storing flow, the volume percentage of which was up to 80%. Although larger pores of tight reservoirs with low transport capability (e.g., sample 2-3) were the dominant flow path, the volume contribution of the smaller pores to storage capacity reached to 70%.
Figure 3 (A) Pore size distribution of the representative elementary volume (REV) of tight rocks, showing pore size followed a power law distribution; (B) Box chart of pore density of different concentric objectives and corresponding porosity of REV.

Conclusions

It is of great importance to investigate the pore microstructure of tight reservoirs for the prediction of transport property. By using the methods proposed, pore microstructure of samples from the Lucaogou Formation of the Jimsar sag were characterized qualitatively and quantitatively in both geometrical and topological properties. Various pore types were identified and dissolution was the main factor to modify pore shapes and pore sizes. Tight reservoirs presented relatively lower heterogeneity of pore spatial distribution and lower exponent of pore size distribution, which were simulated to have high transport flow capability. These tight reservoirs are commonly targeted as sweet spots in the industrial production of tight oil in the Jimsar Sag.

Acknowledgements

We would like to extend our appreciation to PetroChina Xinjiang Oilfield Company of CNPC for the provision of the cored rock samples. Besides, Chunjie Cao and Wen Shi from Zeiss company were appreciated for the help with micro-CT scanning.

References


