

Oil reservoir rock characterization and fluids segmentation using high resolution micro-CT scans

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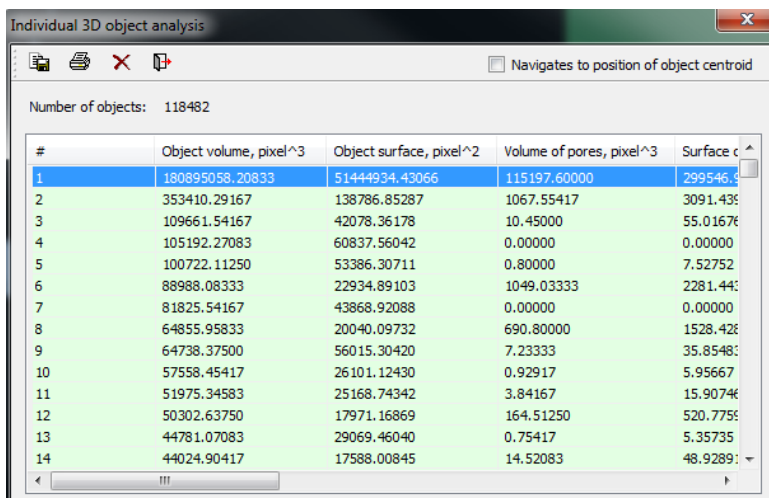
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Objective

Individual 3D analysis (*i3D*) returns the number, *volume* and *volume-equivalent sphere diameter* of the pores in a porous rock sample which is representative of an oil reservoir rock. The cylindrical rock sample has a size of *4mm* in diameter and *6-7mm* in height of which *2.4mm* is scanned in high resolution (*1 μ m/pixel*). The effective pore network at which fluid flow happens is a combination of a huge number of connected pores even in a small sample. *i3D* returns this connected network of pores as a single object. Due to the pores connectivity, the analysis software, *CTAn* (2013 user manual⁴), considers the whole network as a single object (Figure 1). In order to have an accurate measurement of pore sizes we need to separate those pores and find the size of all individual pores constituting the network. The other concern is to find the diameter of the channels connecting the pores in the network. This diameter which is also called throat size is an important parameter in petroleum reservoir engineering. Moreover, accurate segmentation of different fluids (oil and water) which exist inside the pore network of the rock is the third objective of this study.



Individual 3D object analysis

Number of objects: 118482

#	Object volume, pixel ³	Object surface, pixel ²	Volume of pores, pixel ³	Surface area, pixel ²
1	180895058.20833	51444934.43066	115197.60000	299546.9
2	353410.29167	138786.85287	1067.55417	3091.439
3	109661.54167	42078.36178	10.45000	55.01678
4	105192.27083	60837.56042	0.00000	0.00000
5	100722.11250	53386.30711	0.80000	7.52752
6	88988.08333	22934.89103	1049.03333	2281.441
7	81825.54167	43868.92088	0.00000	0.00000
8	64855.95833	20040.09732	690.80000	1528.428
9	64738.37500	56015.30420	7.23333	35.85488
10	57558.45417	26101.12430	0.92917	5.95667
11	51975.34583	25168.74342	3.84167	15.90746
12	50302.63750	17971.16869	164.51250	520.7758
13	44781.07083	29069.46040	0.75417	5.35735
14	44024.90417	17588.00845	14.52083	48.92891

Figure 1: initial *i3D* analysis; object (pore) #1 is the main pore network including several connected pores

Method

Since permeability of the rock sample is low (around 20mD) and there is substantial amount of clay mineral in the structure of the rock which includes large number of very small pores together with the normal pores, a resolution of $1\mu\text{m}$ ($1.04\mu\text{m}$) per pixel was chosen in the *Skyscan 1172D*. The tiny pores are not visible at lower resolutions. The data was reconstructed in *NRecon* and analyzed by means of *CTAn*.

First, the data was pre-processed to remove noise and/or the pores that are not connected to the main network of connected pores.

Further analysis was done on the pre-processed data to extract the pore body and throat size distribution. '*Distance Ordered Homotopic Thinning*' is a method of calculating those parameters. This approach has been used to extract the pore geometry information of an oil reservoir rock sample². Since this method is unavailable in *CTAn*, it is attempted to use the *morphological operations*.

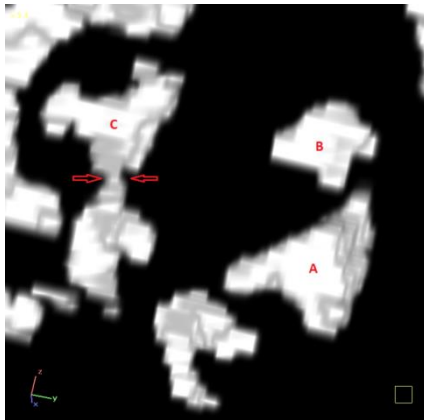


Figure 2: 3D binarised image after *opening* the objects by 12 pixels, objects A and B can be removed (*despeckled*) since they are single pores but object C is still combination of two pores connected by a channel and must be kept in the model for further *open*

There are two options under '*morphological operations*' in '*custom processing*' to separate the connected pores. '*Erosion*' is a function to isolate the connected pores; however since it reduces the size and volume of the pores, it is a destructive function. The other option is the '*open*' function. It includes adding or removing pixels/voxels to or from the surface of all selected binarised objects (Erosion and dilation respectively)⁴. Open means erosion followed by dilation. This function isolates the pores and preserves the pores shape and size to a greater extent compared to the erosion function. Open was run successively starting from radius of 1 pixel ($\approx 1\mu\text{m}$) and continued with radii of 2, 3, 4, 5... pixel until all the pores are disconnected. After every run of *open*, all the isolated pores were removed from the model and saved. Finally, all the saved data from separated pores were assembled in a spreadsheet to find the histogram for frequency of pore size distribution. It should be mentioned that porous media in naturally occurring rocks are often heterogeneous; shapes and sizes of the pores and connecting channels are random to a great extent. Thus the application of the procedure of successive *open* and remove (*'despeckle'*) is not straight forward and in some steps (especially the later steps) more than one object is kept for further *open* in the next steps. For example, in addition to the largest object, the second and/or third largest object after a step of

open may still be a combination of several pores which must be kept in the model for further *open* until all the pores are disconnected effectively. Therefore, after every step of *open* before running *despeckle* to remove and save the disconnected pores, the isolated larger objects must be visually checked in the 3D model to understand whether every one of those objects is a single pore or a combination of some smaller pores (Figure 2). It is adequate to observe the first few large pores. At this point, '*sphericity*' can be used to distinguish if the object (pore) is a combination of several pores as *sphericity* of such an object can be much lower than a single isolated pore due to its higher geometrical deviation from a normal sphere. *Sphericity* of a single isolated pore is much closer to a sphere. This parameter is available in i3D results for every object.

In another study, the *open* function was used to find only pore body size¹, however we use the same function to estimate size of channels connecting the pores as well as size of the pore bodies. Initially, before running any *open*, we have a single object (Network of all connected pores); and in every step of *open*, several objects (pores) are getting disconnected from this network. Since we start the *open* operation from radius of 1 pixel and continue increasing the *open* radius by 1 pixel ($r=1, 2, 3, 4, \dots$), in every step, diameter of the connecting channels for the separated pores is equivalent to two folds of the *open* radius in that step (Figure 3).

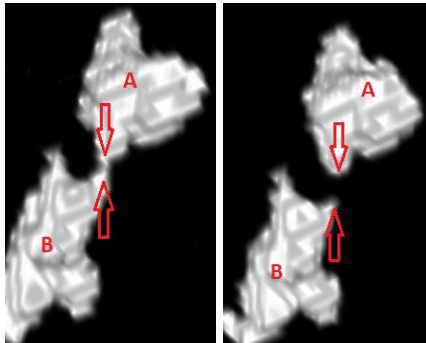


Figure 3: After *open* by radius of 10 (left) and 11 (right); the last *open* eliminates the connecting throat of pores A and B. Thus the diameter of the channel is greater than 20 pixels (20 μm) and equal to or less than 22 pixels (22 μm).

The third step is to distinguish between oil and water inside the pores of a saturated rock. The rock sample is initially vacuumed to remove the air out of the pores. Under vacuum water is imbibed into the pores and the sample becomes 100% water saturated. Afterwards the sample is centrifuged with the crude oil so that the oil replaces most of the water. In this condition, the irreducible water exists together with the oil inside the pores. This simulates the initial condition in an oil reservoir before any oil is produced. The sample is scanned at this condition (*initial condition*). In the next step, to simulate the oil production out of the rock pores, the sample is set inside of a test tube full of water. Therefore water imbibes the pores and replaces some of the oil and pushes the oil out of the rock. This process is called spontaneous imbibition. The sample is scanned after spontaneous imbibition, too (*final condition*). In order to estimate the efficiency of the oil production process the volume of water and oil must be calculated at initial and final conditions for which segmentation of oil and water phases must be done for 3D model.

It was stated that it is common to apply a filter on the data to enhance the peaks of the histogram³. Segmentation was facilitated by applying such filter on the data set in *CTAN* custom processing. Filter with radius of 2 bolds the features (local peaks and troughs) in the histogram of *gray scale index* (or *HU*) frequency. Therefore proper segmentation can be

applied on the model; 2D analysis results were saved for all the images at which 'percent object area' can give the saturation of oil or water depending on the selected interval for gray scale values on the histogram.

$$s_o = \frac{A_o}{A_o + A_w} = \frac{\frac{A_o}{TA}}{\frac{A_o}{TA} + \frac{A_w}{TA}}, \quad s_w = \frac{A_w}{A_o + A_w} = \frac{\frac{A_w}{TA}}{\frac{A_o}{TA} + \frac{A_w}{TA}} = 1 - s_o \quad \text{Equations (1 and 2)}$$

A_o is the area of white pixels in a 2D image while the threshold interval shows oil and A_w is the area of white pixels while threshold interval represents water. s_o and s_w are oil and water saturations respectively. 2D analysis of all images simply returns A_o/TA and A_w/TA which are respectively 'percent object area' of oil and water. This can give the saturation of oil or water vs. depth of the rock sample. Furthermore average value of the oil saturation for all the 2D images – 3D model – at initial and final conditions can be used to estimate the oil recovery efficiency of the process (Equation 3).

$$r = \frac{s_{o,i} - s_{o,f}}{s_{o,i}}, \quad \text{Equation (3)}$$

$s_{o,i}$ and $s_{o,f}$ are average oil saturations respectively at initial and final conditions. r is the recovery.

Results

Figure 4 shows the porosity profile of the cylindrical sample along the z-axis. The average porosity is 12.8%. Object size distribution estimation concluded in average pore body and throat size of 9.9 and 3.7pixel respectively. Moreover the average pore aspect ratio is 2.8 (Table 1). Histograms of pore, throat and aspect ratio are presented in figure 5. Results of oil/water saturation estimation at initial and final conditions are demonstrated in figure 6. As it is shown, oil saturation after imbibition of water into pores of the rock sample is reduced. The difference in saturations of initial and final states can be used to estimate the amount of recovered oil (Equation 3). Average values of saturations are summarized in table 2. 17.4% of the initial oil has been recovered by the imbibition process.

Table 1: Max, Min and average values of size distribution

Parameter	Max	Min	Mean
Pore body diameter (D), pixel	184.7	2.3	9.9
Pore throat diameter (d), pixel	28.0	2.0	3.7
Aspect ratio (D/d), dimensionless	40.7	0.6	2.8

Table 2: Average values of saturations

Phase	Initial saturation (%)	Final saturation (%)
water	31.7	43.6
oil	68.3	56.4

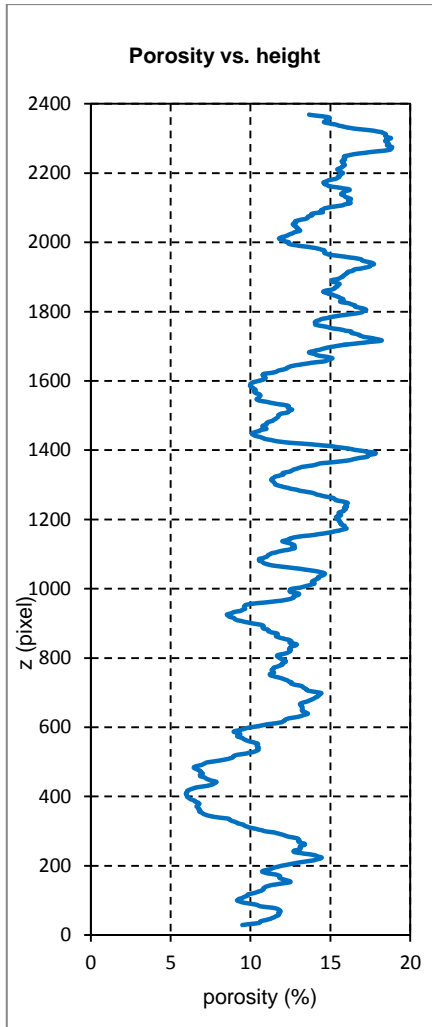


Figure 4: porosity profile of the cylindrical sample in z direction. Average, max and min values are 12.8, 18.9 and 5.9 percent respectively.

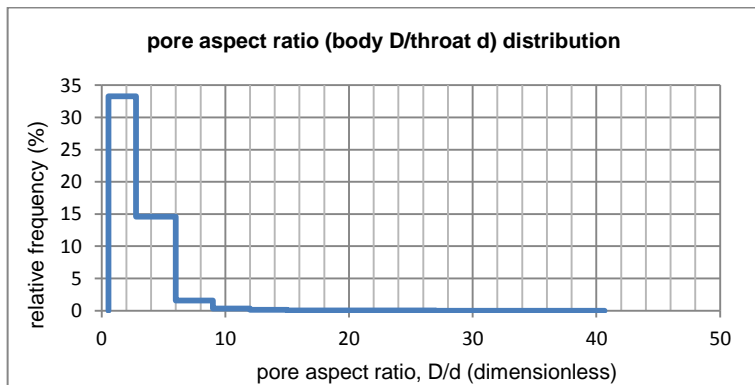
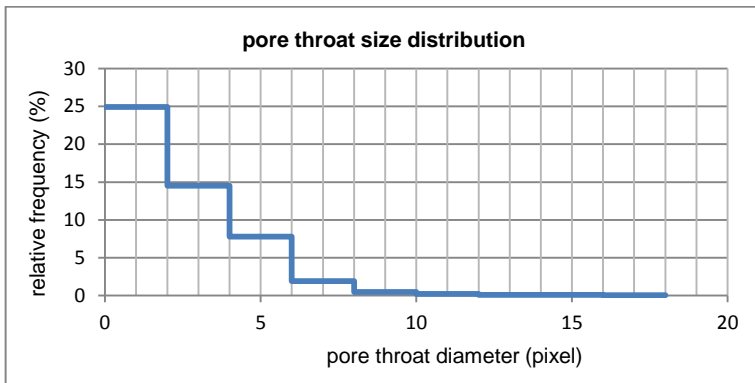
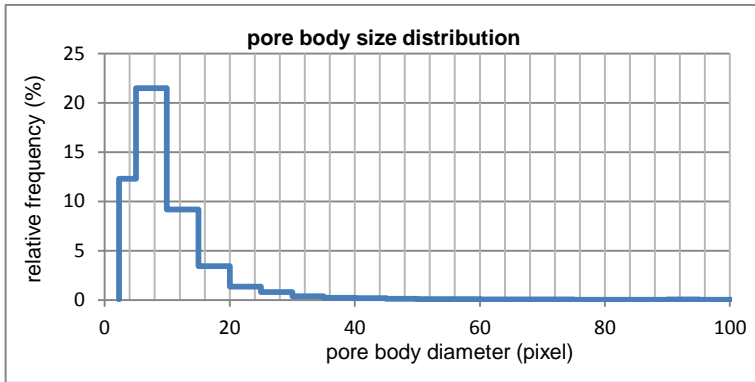


Figure 5: Pore body, throat and aspect ratio size distribution

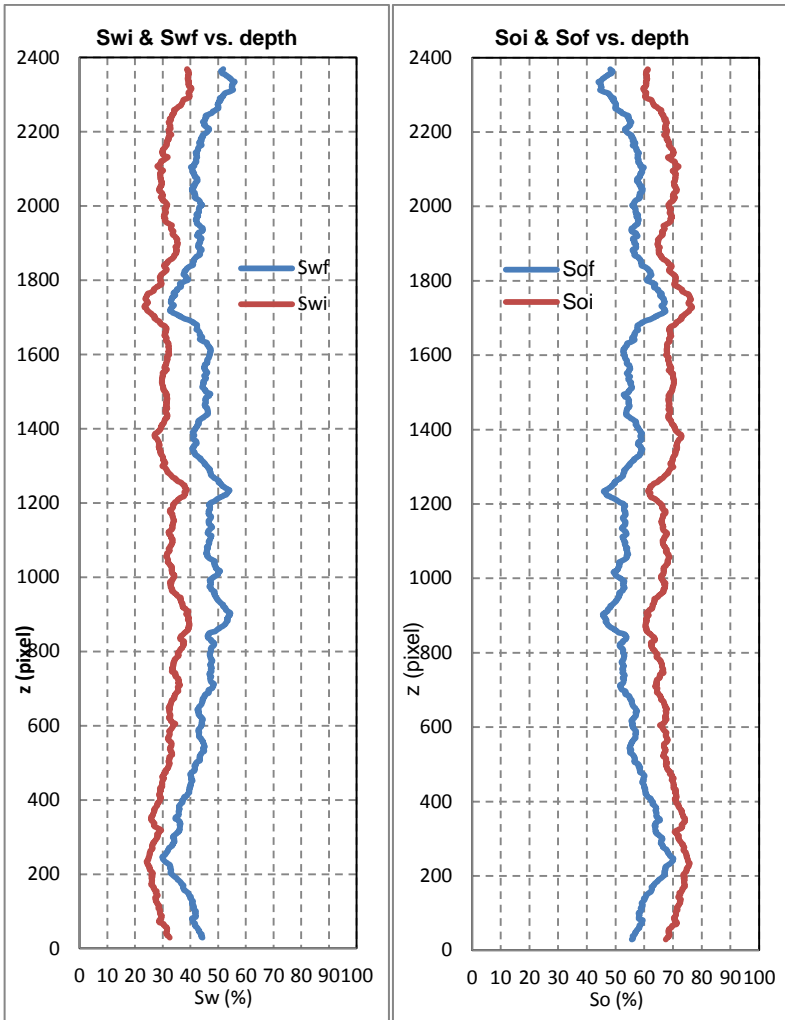


Figure 6: Saturation profiles in z direction at initial (red) and final (blue) conditions

Conclusion

Open is the most appropriate morphological function to simultaneously obtain pore body, throat and aspect ratio size distribution. Also, based on our knowledge, this is the first time throat size has been determined by successive *opening* of pores. Furthermore, μ -CT is a good tool for micro-scale characterization of oil reservoir rock and fluid saturation measurement which leads to micro-scale quantification of oil recovery performance of different recovery processes.

Acknowledgement

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