# Permeability Prediction and Network Extraction from Pore Space Images

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## 1. ABSTRACT

A methodology for extracting networks from pore space images is presented. It computes the location and sizes of pores and throats to create a topologically equivalent representation of the void space of 3D rock images, using the concept of maximal balls (Silin et al., 2003). The model is successfully tested on both sandstone and carbonate samples. The network extracted from a Fontainebleau sandstone sample yielded a coordination number distribution that agrees well with a distribution measured on a model that reproduced the sedimentary processes by which the sandstone was formed (Øren and Bakke, 2003). The model was further tested on a Berea sandstone sample and a carbonate sample from subsurface Oman. The computed absolute permeabilities, using the extracted networks, agree well with the measured value for all samples.

## 2. NEW NETWORK EXTRACTION TECHNIQUE

A new pore network extraction algorithm has been devised overcoming some of the limitations of previous approaches (*Lindquist and Venkatarangan 1999, Delerue and Perrie, 2002, Knackstedt et al, 2004 and Al-Raoush et al., 2003*). The algorithm uses the maximal ball concept originally described by Silin et al. (2003), but is extended to provide a definition of throats and extracts a complete network.

The new algorithm was tested on two sandstone samples (Fontainebleau and Berea) and one carbonate sample from subsurface Oman. The Fontainebleau sandstone sample is in the form of a 3D image: a cube of size 2.25 mm with an image resolution of 7.5 µm ($300^3$ total voxels). The image was obtained from a process-based model; in this case a network obtained from knowing the location of the grain centers is also available for comparison (*Øren and Bakke, 2003*). The Berea sandstone sample is also in the form of a 3D image: a cube of size 1.28 mm with an image resolution of 10 µm ($128^3$ total voxels), obtained from micro-CT scanning (*Dunsmuir et al., 1991; Hazlett, 1995*). The carbonate sample is borrowed from Petroleum Development Oman and, unlike the above two samples, is derived from a 2D image extracted from a subsurface carbonate core plug. The image represents a small part of the 2D thin section of the core plug. The 2D image was then transformed into a 3D image using multiple point statistics (*Okabe and Blunt, 2004*).

The three networks, extracted from the three pore space images discussed above, are compared first with previously computed data, using other process-based network models, and second with laboratory measured data. Due to the limited size of this paper, the results for the Fontainebleau sample analysis will only be given here.

### 2.1. Extracting a pore network model from the Fontainebleau sandstone 3D image

The Fontainebleau 2.25mm (300 voxels), 3D image (Figure 1) was sliced into 4 by 4 by 4 cubical portions (sub-images), giving rise to 64 portions in total. Only the central 12 portions were used in this analysis.

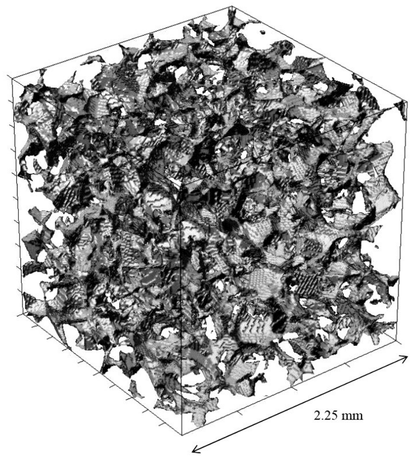


FIGURE 1: A 3D pore-space image of the Fontainebleau sandstone. The pore space is shown in grey. The image was generated using a process-based model with a resolution of 7.5µm.

Network properties for each of the 12 3D images were computed. The algorithm cannot handle the entire 3D image in one go using a standard 2GB PC due to computer time and memory limitations. Figure 2 shows one of the 12 extracted networks.

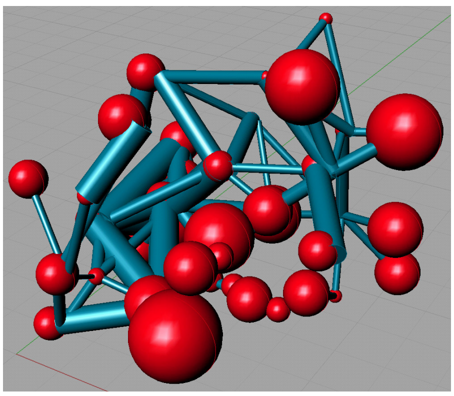

FIGURE 2: Three-dimensional image of the extracted pore network for the Fontainebleau image ($75^3$ voxels).

The properties of the extracted networks averaged over all 12 Fontainebleau images are compared to the properties of the network derived from the process-based technique of Øren and Bakke (*2003*) in Table 1.

TABLE 1: Properties of the network extracted from 12 central cubical portions of the original 2.25mm, 3D Fontainebleau image.

| | This work (averaged) | Øren and Bakke (2003) |
|---|---|---|
| Size of image (mm): | 0.56 | 2.25 |
| Volume of image ($mm^3$): | 0.18 | 11.39 |
| Number of pores: | 52 | 4997 |
| Number of throats: | 116 | 8192 |
| Average connection number: | 4.1 (3.3 to 4.9) | 3.2 |
| Number of connections to inlet: | 9 | 227 |
| Number of connections to outlet: | 7 | 206 |
| Median throat length to radius ratio: | 12.5 | 8.7 |
| Net porosity (%): | 13.2 | 13.6 |
| Absolute permeability (mD): | 538 | 582 |
| Formation factor: | 34 | 35 |

The resulting pore throat size distribution is compared with that derived by Øren and Bakke (*2003*), Figures 3.

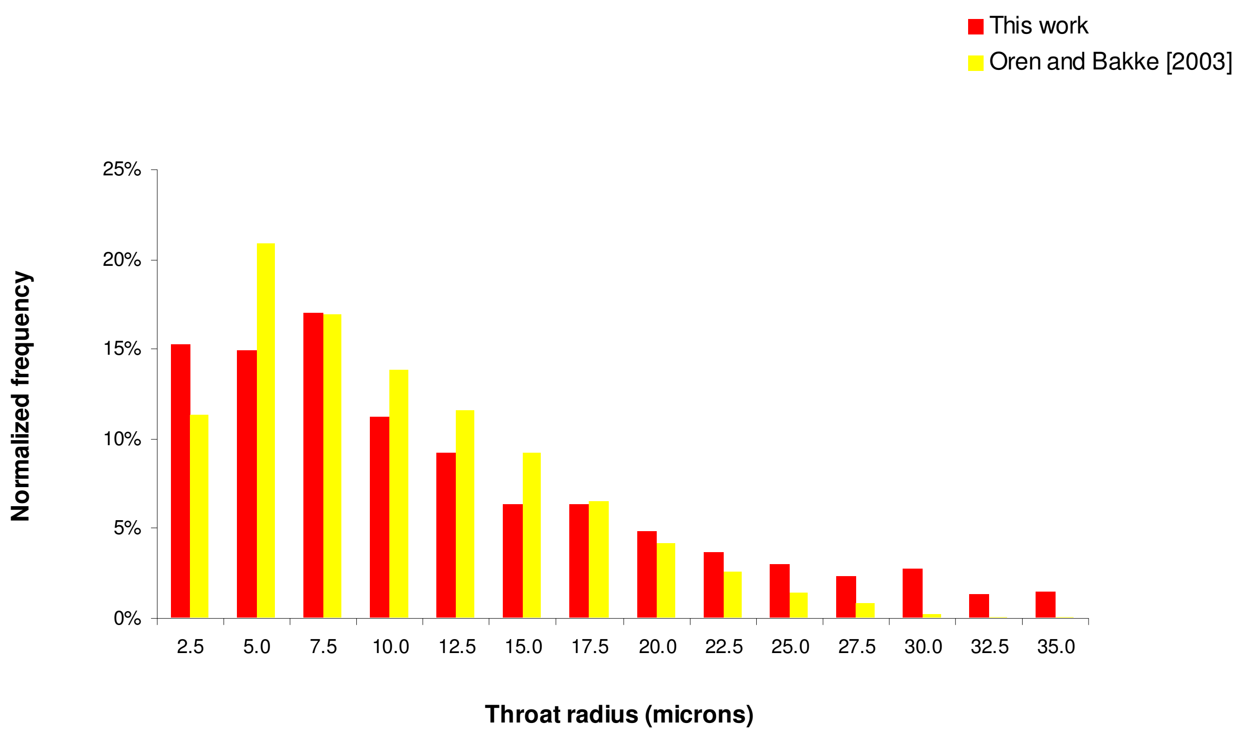


FIGURE 3: Pore throat size distribution for the Fontainebleau sample compared to the work of Øren and Bakke (*2003*).

The pore throat size distributions from the extracted network and the process-based model match well (Figure 3). The coordination number distribution generated using the central Fontainebleau portions combined is plotted against the results from Øren and Bakke (*2003*) in Figure 4.

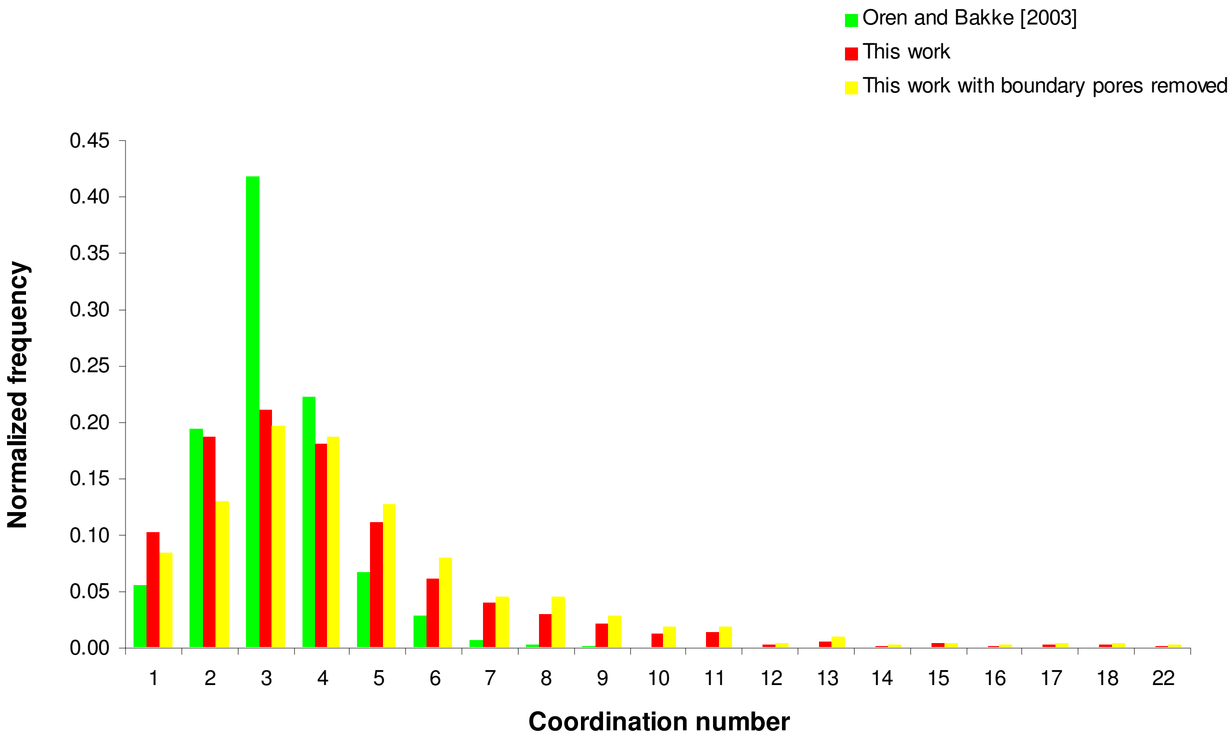


Figure 4: Coordination number distribution for the Fontainebleau sample compared to the work of Øren and Bakke (*2003*).

The coordination number distribution compares well with that derived from the process-based network. The removal of boundary pores reduced the number of pores with small connections, as one would expect. In fact the removal of boundary pores made the distribution sharper at low connection numbers, leading to a better comparison with the distribution generated by Øren and Bakke. It is clear that both techniques yield the same mode coordination number of 3, Figure 4.

**2.2. Comparison with core plug measured porosity and absolute permeability**

The porosity and absolute permeability computed from the extracted Fontainebleau network models are compared with the core plug laboratory measured values (Table 2). It should be noted that the experimental measurements are made on core plugs typically 1cm across and which are consequently much larger than the networks, micro-CT or SEM images.

TABLE 2: Comparison with measured properties for the Fontainebleau sample.

| Fontainebleau sample | Network model (this work) | Network model (Øren & Bakke - 2003) | Experimental (core plug) |
|---|---|---|---|
| Porosity computed in extracted networks or measured experimentally using a core plug sample | 13.2 % | 13.6 % | 14.8 % |
| Permeability computed in extracted networks or measured experimentally using a core plug sample | 538 mD | 582 mD | 1400 mD |
| Permeability calculated on image, by Okabe, using the Lattice Boltzmann method (Okabe and Blunt, 2004) | 956 mD | | |

The network derived absolute permeability is lower than that measured in the core plug, probably due to the heterogeneity in the core plug, as seen by the pore size distribution and the connection number analysis. However, the two network models, although derived from two different techniques, compute very similar values for the absolute permeability. The difference in absolute permeability with core plug measured values is not large. The extraction of multiple network models from the same core plug may lead to a better convergence of the network results towards the experimental values.

## 2.3. Trial to combine small networks to generate a large network

A new technique was devised in this work to combine small network models into one larger model to enable better predictions of absolute permeability and further to facilitate relative permeability predictions. Although this work is ongoing but first results are shown here.

The trial was conducted on the Fontainebleau sandstone sample where the entire 2.25mm sample, discussed above, is now sliced into 27 cubic portions (Figure 5).

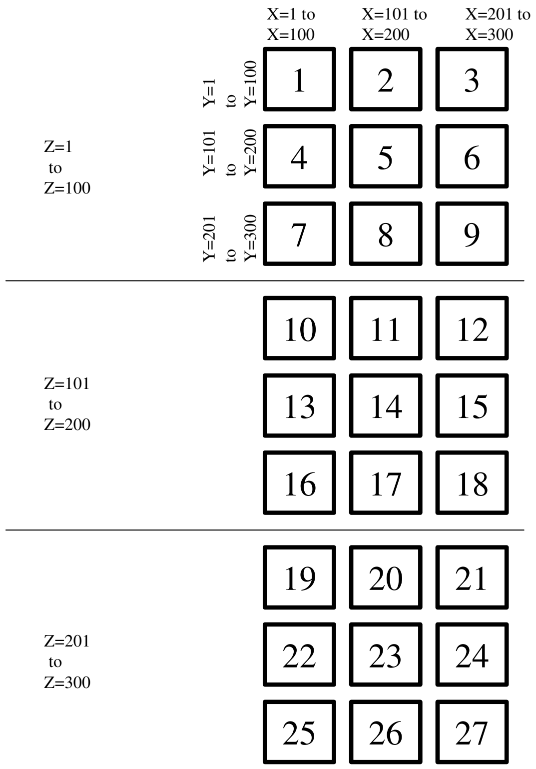


FIGURE 5: Schematic drawing showing the distribution of the 27 networks comprising the full 3D Fontainebleau image (300 voxels by 300 voxels by 300 voxels).

The size of each cube is 0.75mm or 100 voxels in each direction. 27 network models were generated and were then combined to form a large network model of size 2.25mm. The 27 networks were combined in such away that 5% of the nodes at each of the six faces of each network are manually connected to the equivalent nodes of the opposite face from all surrounding networks.

Each node from one face of the network is connected to all the nodes at the opposite face of the other network. To generate the full image, the combining procedure had to be applied in 3D to connect networks that are in all X, Y and Z directions and were executed in six main steps (Figure 6).

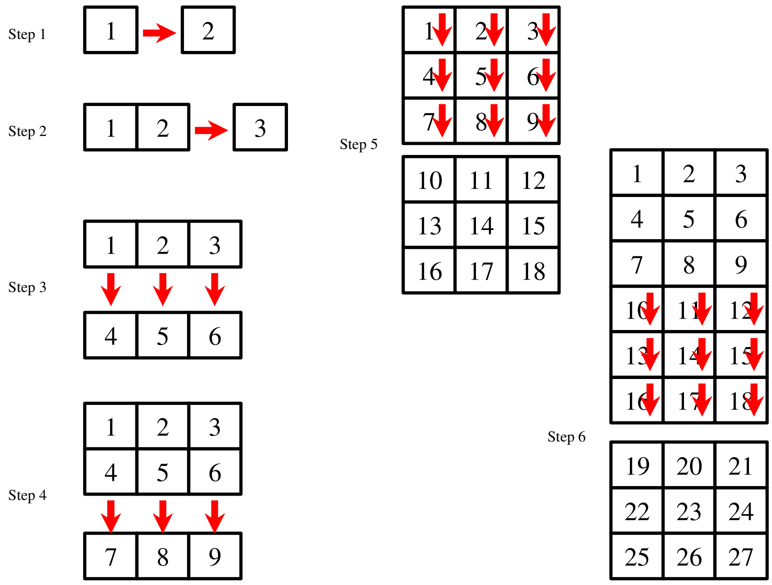


Figure 6: Schematic drawing showing the main steps taken during the network combining procedure.

Preliminary results indicate that the absolute permeability of this new combined and large Fontainebleau network is 1270 mDarcy. This is in good agreement with the measured core plug permeability of 1400 mDarcy, from which the network model is extracted. Furthermore the porosity computed for the new large network is 14.8% which is what has exactly been measured for the core plug.

## 3. CONCLUSIONS AND FUTURE WORK

An algorithm for network extraction is presented based on the maximal balls concept of Silin et al. (2003). Methods for determining pores and throats were presented. The extracted sandstone networks were compared with those generated based on a process-based model and the results were similar. The advantage of this approach is that it can be applied to any image, without requiring the grain centers to be known. It is a complementary technique to medial axis analysis (Lindquist and Lee, 1996).

Three samples were investigated in this study: two sandstones and one carbonate. Network models were successfully extracted from 3D and 2D pore space images. The computed coordination number distribution, and pore and throat size distributions compared well with results from process-based networks (Øren and Bakke, 2003). Furthermore, the porosity and absolute permeability compare well with measured core plug values as well as values obtained from Lattice Boltzmann calculations performed directly on the 3D image.

The present algorithm precludes the extraction of large networks using standard computer resources. Further work is required to extract networks of sufficient size to make reliable predictions of single and multiphase flow properties. One way to do this will be to enhance the new algorithm with a parallel processing capability. Another way which has been investigated and was briefly presented here is to combine or patch small networks together to generate a network of sufficient size to undergo reasonable computations of multi-fluid flow.

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