Chemical Process Design Vol.2 No.1 (2023) 6-31

University of Sistan and Baluchestan

Chemical Process Design

Available online at http://cpd.usb.ac.ir/



A Comprehensive Review of Digital Rock Physics: From Tomographic Images to Pore Network Modeling

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ARTICLE INFO

Article history:
Received: 2023-03-13
Received in revised form: 2023-05-28
Accepted: 2023-06-15
Published online: 2023-06-23

Keywords:
Pore network modeling; Digital rock Physics; Porous media; Reconstruction Algorithms; Open PNM

DOI: *10.22111/CPD.2023.44680.1018*

ABSTRACT

The growth of hydrocarbon resources dramatically influences the energy market's future. Digital Rock Physics (DRP) is a scientifically accepted approach for evaluating reservoirs' rock qualities. In theory, knowing the geographical distribution of the linked pore space enables one to anticipate the characteristics of a rock sample. But upscaling predictions systematically hasn't been possible yet due to restrictions on unique microscopic resolution and approximated measurements. Getting information about the structure through tomographic pictures of porous materials is an essential part of porous media investigation. The ability to extract pore networks is especially beneficial because it allows for pore network modeling simulation studies, which can also be helpful for various tasks ranging from modeling transportation characteristics to predicting the effectiveness of the whole equipment. This paper deals with a comprehensive overview of the importance, steps and methods of simulating the porous medium using pore network modeling and all their necessary prerequisites. For this purpose, instead of using continuum-based modeling it has been tried to enter in the pore scale and review the steps of modeling that happen in that according to image-based methods mentioned by previous researchers, which are very useful for modeling complex geological materials.

1. Introduction

Porous materials are essential in a wide range of technologies and companies. In oil recovery and aquifer management framework, naturally existing porous media like rock and soil have become the topic of much research [1]. Engineered or produced porous materials have allowed advancements in various sectors, including electrodes [2], membranes [3], biological applications [4], and others [5]. Designing porous materials is a typical optimization problem: the existence of the solid is required to supply some critical operation, such as reactive surface region, whereas it also

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generates flow and transport impediments. The pore structure may significantly influence transport processes, which is a distinguishing property of all porous materials. The transport qualities of two substances with comparable porosities will change considerably, relying on how the pores are spatially dispersed, how they are linked, their morphologies, size distribution, and so on. Because of how crucial pore structure is to the investigation of porous media, visualization is an essential technique. Because it offers views of the interior structure, high-resolution x-ray tomography is very valuable [6]. Benchtop x-ray tomography scanners with 1-m voxel resolution are now commonly accessible, and the newest generation can acquire images with a resolution of 100 nanometers or less [7]. Extracting the enormous amount of data contained in such images is a laborious process [8].

Multiple schools of study have devoted considerable time and energy to investigating the potential symbolism of a porous structure, including a network of holes and throats [9, 10]. To quantify the flow and transport processes occurring in a porous media, it is crucial to precisely depict its form, which has become ever more relevant as pore-scale modeling has evolved [11-13]. The interior structure, shape, and size of pore bodies or enormous empty spaces may all provide insight into pore connectivity (geometry). Narrow passageways connect these enormous vacuum zones termed throat bodies, which may also be considered examples of pore connection [14]. For a porous substance to be mapped onto a network of pores and throats, the person performing the mapping must first define what a pore and a throat are and when and where pore-throat constrictions meet [15]. This is due to the many possibilities of contact between a pore and a throat. The size and length distributions of pores and throats are two microstructural features that may be affected by the macroscopic parameters of porous media, such as permeability, effective fluid diffusivity, and pore stoichiometry [7]. Certain features of the microstructure do not correspond to this description. Several transport techniques may be employed to construct a network of pores and throats that is a decent model of the overall system, allowing researchers to come near to these large-scale aspects. Knowing the exact structure of the porous material is essential before cutting a series of holes and throats into it.

The article reviews the history of digital rock, from its origins in the study of porous media to its development into a practical tool for the petroleum industry. As we discuss the features of digital rock, we will provide you with a brief introduction to the application of X-ray microcomputed tomography as well as through the use of pore-scale modeling, both of which are used for studying rock samples at the pore-scale. Digital rock is explored from both a philosophical and scientific perspective, emphasizing the importance of understanding the fundamental physics of fluid flow in porous media as well as the importance of the theory behind the invention. In this paper, electronic rock will be discussed in relation to its applications to a variety of fields in the petroleum industry, including the characterization of reservoirs, the simulation of fluid flows, and the enhancement of oil recovery. Digital rock has both advantages and limitations, highlighting the importance of carefully interpreting the results and the need for complementary laboratory techniques to complement these findings. It is also discussed how pore network modeling can be used in the field of digital rock technology in order to simulate fluid flow in porous media at the pore level, which is a very useful method for analyzing fluid flow in porous media. In summary, digital rock technology, which includes pore network modeling, constitutes an important tool in the oil and gas industry that is capable of improving the understanding of reservoir rocks and enhancing a reservoir's ability to recover hydrocarbons.

2. Choice of spherical grains to construct the porous media

The use of spherical grains as model building blocks simplifies the modeling of porous media. There won't be much arduous job for you to complete. Bryant et al. [16] created the pore network and evaluated the permeability of a mono-dispersed packing of spherical grains using Delaunay tessellation. Bryant et al. [17, 18] were able to produce a more realistic grain packing by allowing evenly inflated spherical grains to overlap while moving them vertically. By simulating compaction, they were able to duplicate the quartz cementation process. This made it possible to simulate the quartz cementation process [18]. The spherical and ellipsoidal grains of the Berea sandstone were modeled by Oren and Bakke using a process-based methodology. They tested their model using flow simulations. The models of Ren and Bakke took into account spheres of various diameters as well as the gradual accumulation of grains in a gravitational field (sedimentation), the vertical movement and overlapping of grains (compaction), and the static swelling of grains brought on by the entry of quartz/clay contents (diagenesis) [19, 20]. They admitted that using spheres as the sole grain form in their model was a limitation, but they did point out that in the absence of porosity fluctuation, grain shapes often didn't make a significant difference when estimating permeability. Distinct Element Analysis and Pore-Network Simulations: Integrating the Distinct Element Method (DEM) with the Pore Network Model is an additional cutting-edge strategy for investigating the effects of geomechanical deformations on the flow characteristics of porous media (PNM) [21]. Much research has not been done on the utilization of coupled hydro-mechanical techniques at various scale levels, such as those found in petroleum engineering and hydrogeology applications. Excitingly, Manchanda et al. [21] used DEM and PNM to record the alteration in permeability while a sample was put through a shearing procedure. To include the particle form into a model constructed with spherical grains, they devised the necessary strategies for doing so. Instead of using individual spherical grains, "clumps" might be constructed to depict the particles of interest. When more than one spherical pebble is clumped together, they behave as if they were a single, unified entity despite its complicated, non-spherical form (Itasca 2018). Similar to how porous media may be created from either permeable or impermeable spherical grains, clumps can be distributed to create a porous medium (Fig. 1).

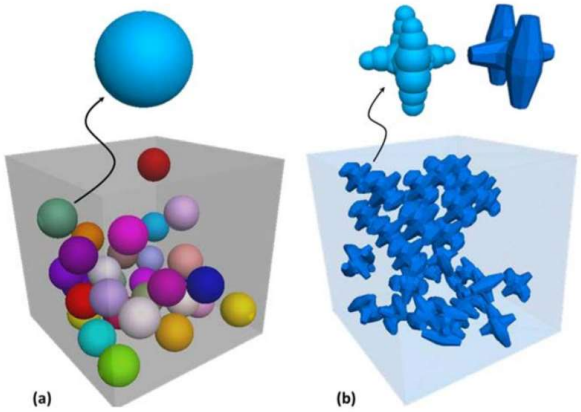


Fig. 1. Generating porous medium by distributing (a) sets of balls and (b) sets of clumps in PFC3D [22]

In this study, Raziperchikolaee and coworkers examined how seismic source processes relate to the permeability of fractured rock joints [23] using a pore-flow-chart (PFC) and pore network modeling to essential volume components of a sample. The purpose of this was to understand the relationship between the two betters. Mechanical data gathered

from packed sand and sandstone rocks were used to improve the DEM model. Research into the permeability of deformed rock joints was conducted, for this reason, hoping to learn more about the mechanisms at play in the genesis of seismic activity. (REV). It was possible to reconstruct the pore network and simulate fluid flow through the sample after subjecting it to a predefined stress route. Because of this, we were able to model fluid dynamics. During their investigation of the sliding failure mechanism of faults, Yang and Juanes [24] revealed the importance of pore pressure. To do this, they built a pore network flow model that could accurately represent the behavior of many spherical elements moving in close proximity to one another inside a discrete element method (DEM) simulator.

3. The importance of using digital rock physics compared to conventional methods

Darcy's rule, or any of the many other methods that are functionally equivalent, may be used to provide an accurate portrayal of the flow at the continuous scale. Both of these approaches may be used to provide a reliable image of the flow. When integrated, these strategies might provide a more comprehensive strategy. However, the properties of porous media, such as porosity, relative permeability, capillary pressure correlations, and so on, considerably affect the accuracy of their predictions [25]. The proportion of a medium that is composed of microscopic holes is known as its porosity. Our understanding of flow in porous media has progressed in recent years due to the introduction of rock imaging technologies that reveal porous rock and the fluids that are trapped inside it. The growth may be attributed to the development of these technologies. These technologies were developed in recent years. Research experiments are now being carried out, with these characteristics serving as the focus of the investigations. In order to provide an accurate representation of the flow that takes place in these materials, we combine this technique with open-source numerical methods [26]. When attempting to evaluate the transport properties of carbonates with a complicated structure, the typical correlations do not provide sufficient information, and tight sandstones are examples of geological materials with pores of several sizes. The matrix of multimodal pore-size distribution vugular carbonates is on the nanometer/micrometer scale, and the vugs themselves may be anywhere from one the range in size from the micrometer to several millimeters [27]. Although modeling and simulating multiphase flow in multimodal carbonate rocks is still a big open issue, it is crucial because a large proportion of the world's hydrocarbon reserves are stored in such reservoirs [28].Consequently, it is essential to investigate such rugged rocks at the pore scale and utilize appropriate physics for transportation possessions [29].

The image-based approach comprises directly collecting pore networks from X-ray photos, such as computed tomography (CT) images or numerical porous material structures. Other examples of these types of pictures are CAT scans. Image-based methods need the availability of micro-CT or other X-ray-based imaging equipment in order to obtain a three-dimensional (3-D) picture of the porous material. To build the pore network, a 3-D picture is subjected to an extraction technique [30, 31]. Cropping, noise reduction, and phase segmentation are among the image processing methods used to prepare 3-D pictures meticulously. Following this step, the technique for extracting pore networks is used to construct a three-dimensional network of pores and throats. In a manner that corresponds to the integrated and vacant spaces of the binary pictures. Lindquist et al. [16] developed a technique for designing and building using CT scans in order to evaluate the geometric tortuosity and distribution of linked and unconnected pores in sandstone measurements. As a result of this approach, studies have discovered the central axis of the pore structure, also known as the topological framing [32].

There are numerous techniques for extracting the pore network from CT images [33]. Research on two-phase flow (gas and water) as well as more recent researches have demonstrated that the maximum ball method has wider applicability. This methodology was used by the writers Silin and Patzek [34]. The optimum ball method was later improved upon by AlKharusi and Blunt [30], who carried out tests on sandstones and carbonates with great results. The maximal ball method results in the production of a number of spheres inside the pore space. Large spheres are used to represent pores in the diagrams. Throats are small spheres that connect larger spheres. Smaller spheres placed in between the larger ones create cylinder-shaped "throats.". As a direct consequence of this, the maximum ball method is used in order to extract the pore network from 3D CT scans. This pore network consists of pores (which are spheres) and throats, which are cylinders [26, 35]. By examining the derivation of transport equations and created pore networks [36], Properties that are measurable and capable of being examined include capillary pressure, absolute permeability, and relative permeability, respectively. Absolute permeability should not be confused with relative permeability; the two concepts are separate from one another. Performing this study in a more hands-on manner is an option. The numerous different approaches that may be used to determine transport characteristics using PNM are shown in Fig. 2, which can be found below.

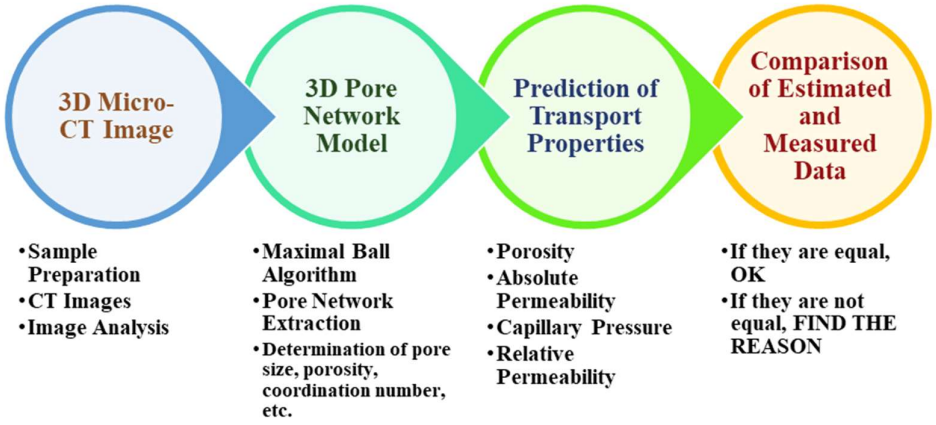


Fig. 2. The procedures to estimate transport properties by pore network modelling [37]

Micro-scale x-ray calculating imaging technology, also known as xCT, is a relatively new technique for three-dimensional imaging of pore architecture. This imaging method takes pictures of rock samples with a resolution that is as low as simple enough to be evaluated in tens or hundreds of nanometers (voxel size) (physical resolution). Scanning of the internal framework of finely structured materials may be accomplished with pinpoint accuracy and without causing any damage using xCT. After removing xCT scanning artifacts and performing fragmentation, the scan is then processed in such a way as to preserve the petrophysical features of the materials [38, 39].

- Identifying characteristics of transportation, such as absolute and relative permeability [40-42].
- The calculation of the electric and elastic characteristics of the Earth's geology and geotechnology, as well as the NMR response [43].
- Doing research on methods for better oil recovery [44].
- Determining whether or if the use of pharmacological treatment for well stimulus has the potential to be successful [45].

Digital core analysis poses new challenges to conventional reservoir techniques, especially due to the complex and multiscale nature of shale gas transport. Many reconstruction methods cannot be applied because of multiscale complicated pore systems. A key part of pore structure and mineral component characterization is high-precision imaging. Shale digital rock reconstruction has been made possible by physical experimental methods and hybrid superposition methods, but rapidly evolving deep learning methods are also promising. Indirect modeling can be performed using pore network models or digital rock techniques to simulate the pore-scale flow of shale gas. By considering desorption, surface diffusion, and slippage in nanopores, shale gas flow can be precisely and realistically investigated. Research in off-mentioned methods and processes has recently advanced and Yang et al. reviewed the recent advances [46].

4. Comparison of direct pore modeling with pore network modeling

In recent years, the estimation of fluid flow in petroleum engineering has seen significant use of two methodologies: direct pore simulation (DPS) [47] and pore network models (PNMs) [48]. The sources that are given below include information about both of these approaches. In order to facilitate direct solution of the governing transport equations at the pore scale, the domain is now undergoing gridding using the DPS technique (also known as direct pore modeling or direct numerical simulation). The Stokes flow [49, 50] and the Lattice Boltzmann method (LBM) for solving the Boltzman equation both serve as the basis for many CFD processes. In addition, the Lattice Boltzmann method that solves the Boltzman equation also serves as the foundation for the Lattice Boltzmann method [51-53]. In addition, the Boltzman equation-solving Lattice Boltzmann technique is based on the Lattice Boltzmann method (LBM), which serves as the basis for the (LBM).While the former uses a numerical Navier-Stokes solution [54, 55], the latter uses a kinetics-based methodology that may statistically produce the same answer [56-58]. DFS can tackle a wide range of complex multi-scale multi-physics phenomena, such as diffusion, sorption, and reactive transport, combined with advective one-phase or multiphase fluid flow [59-62]. Direct numerical simulations are often used if a porous medium is treated as a volume-averaged continuum without identifying its micro-scale properties. Due to their mathematical complexity, continuum models are not always applicable in practice. For instance, macroscopic transport characteristics in porous media require experimental measurements of relevant correlations [63]. Multiphase flow makes it more difficult to quantify parameters like permeability coefficient and effective diffusivity. Second, in volume-averaged continuum modeling, the discrete pore-scale events are not identified; therefore, the model estimates the overall fluid volume. Therefore, we need more thorough formulations than those based on extensions of Darcy's rule for multiphase flow to accurately anticipate how the fluids would be distributed throughout the continuum. Although this problem is addressed by pore network modeling [64], the complex mathematical formulas necessary for solving it are removed. The PNM method is a popular alternative to DPS [65]. As an alternative to direct numerical simulation (DNS), pore network modeling (PNM) provides various benefits via the use of simplified assumptions. Compared to DNS, PNM requires substantially less processing power and can control millions of pores instead of thousands. Moreover, PNM makes it simple to simulate static multiphase flows, much as DNS does.

PNMs, on the other hand, are in a position to overcome the problems that are associated with continuum structures, despite the fact that this comes at the expense of some mathematical soundness. This technique represents the pore space as a network of pipes instead of modeling it as a system of partial differential equations (PDEs) of arbitrary

order. The simulation of transport inside a network uses finite difference techniques, which offer an approximation of 1D analytical solutions to the essential transport equations. These solutions are employed in the simulation of transport within the network. Although this simplification was made, PNMs can forecast different elements of multiphase transport with a high degree of accuracy and speed [40]. We take into account the dynamic relationship that exists between geometry and the dynamics of fluid flow by tailoring the sizes of the pores and throats as well as the connections between them to the observed physical structure. This allows us to take into account the dynamic relationship that exists between geometry and the dynamics of fluid flow. Imaging techniques [35, 66] and computer-generated structures [49, 51] are two ways that may be used to quickly assess the structural features of the porous material. Both of these approaches can be found in the references listed above. In order to get the model closer to the observed values of the experimental parameters [17, 67, 68], it is probable that the pore and throat diameters will need to be subjected to some possibly modest modifications. Because of their inherent aptitude for percolation calculations [69], PNMs can recreate realistic fluid invasion processes with very little effort on the part of the computer [70]. This capacity is made possible by the PNMs' ability to duplicate realistic fluid invasion processes. This permits descriptions of the fluid distribution inside the materials at the pore size, which has far-reaching ramifications for almost all of the other transport processes. These descriptions may be used to determine how fluids move through materials. The predictive network models, also known as PNMs, tend to characterize pores and throats as being closed off to other phases when they are filled with one phase [71]. In addition to this, PNMs have the capacity to provide predictions about constitutive connections for multiphase parameters that are not obtainable by experiment [72-74]. You may find in-depth analyses of pore network modeling as well as comparisons of approaches in the published literature [1, 12, 75]. Fig. 3, which may be seen in its entirety by clicking on this link, depicts the pores and throats of a single sample of a produced porous medium in three dimensions.

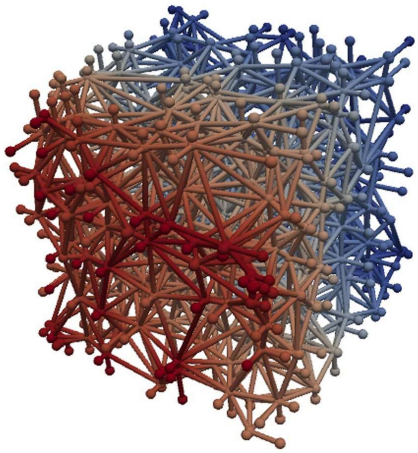
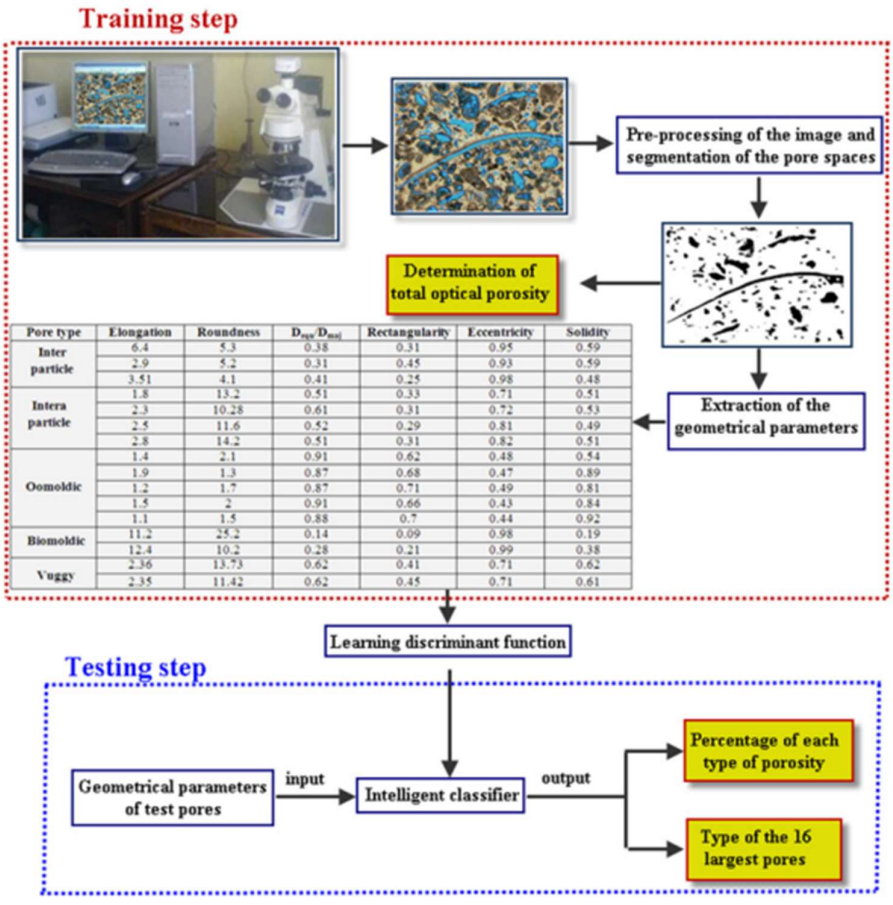


Fig. 3. Pore and throat network interconnected in the porous media [76]

The sole commercially available software is PoreXpert, developed by a Plymouth University team and was initially known as Pore-Cor [77]. However, teams may sometimes give overviews of their internal code [78]. In contrast to computational fluid dynamics, where several robust commercial and open-source solutions exist [79], to the best of our knowledge, no other initiatives are underway to build an open-source PNM framework. Researchers in the PNM community often write their code for usage inside their lab. Frequently, the present code is not adequately documented for future users, and it may not be optimized for performance, modularity, extension, or maintenance. This

necessitates a significant investment of time and money. These are, unfortunately, typical issues that prompted the creation of OpenPNM. The goal is to provide the porous media community with a single, robust, and adaptable set of tools to solve any PNM issue. Researchers will be able to share their code, model comparisons will have a standard against which they can be compared, and we can all build upon the efforts of our predecessors, speeding up the pace of study and discovery.

Ghiasi-Freez et al. introduce a model for semi-automatic identification of porosity types within thin section images using a pattern recognition algorithm. Six geometrical shape parameters of sixteen largest pores of each image are extracted using image analysis techniques and used for training two intelligent discriminant classifiers. The classifiers take the geometrical features of the pores to identify the type and percentage of five types of porosity, including interparticle, intraparticle, oomoldic, biomoldic, and vuggy. The accuracy of the classifiers is determined from two standpoints: the predicted and measured percentages of each type of porosity are compared with each other and the precisions of classifiers for categorizing the pore spaces are analyzed. The proposed methodology is a further promising application for petroleum geologists allowing statistical study of pore types in a rapid and accurate way [80]. Fig. 4 shows a comprehensive flow chart of the semi-automated model.



Pore type	Elongation	Roundness	D_{min}/D_{max}	Rectangularity	Eccentricity	Solidity
Inter particle	6.4	5.3	0.38	0.31	0.95	0.59
	2.9	5.2	0.31	0.45	0.93	0.59
	3.51	4.1	0.41	0.25	0.98	0.48
Intera particle	1.8	13.2	0.51	0.33	0.71	0.51
	2.3	10.28	0.61	0.31	0.72	0.53
	2.5	11.6	0.52	0.29	0.81	0.49
	2.8	14.2	0.51	0.31	0.82	0.51
Oomoldic	1.4	2.1	0.91	0.62	0.48	0.54
	1.9	1.3	0.87	0.68	0.47	0.89
	1.2	1.7	0.87	0.71	0.49	0.81
	1.5	2	0.91	0.66	0.43	0.84
	1.1	1.5	0.88	0.7	0.44	0.92
Biomoldic	11.2	25.2	0.14	0.09	0.98	0.19
	12.4	10.2	0.28	0.21	0.99	0.38
Vuggy	2.36	13.73	0.62	0.41	0.71	0.62
	2.35	11.42	0.62	0.45	0.71	0.61

Fig. 4. A flow chart of semi-automated model for identifying porosity types [80]

Sharifi proposes an accurate yet cost- and time-efficient intelligent framework to measure pore space based on digital rock physics. Total pore space was calculated after estimating the pore geometry through pattern recognition on thin-

section images captured through polarized-light microscopy. Three different multi-class classifiers (radial basis function, support vector machine and k-nearest neighbours) were used to estimate pore type and aspect ratio. An artificial neural network was applied to interpolate discrete data points (thin sections) into continuous profiles of pore type and aspect ratio. The proposed approaches were applied to a real-world carbonate reservoir for modelling the P and Swave velocities through a rock physics model. The most significant advantage of the intelligent pore type quantification over conventional methods was found to be its ability to estimate elastic properties with good accuracy. The key findings of this research include automatic detection of the pore types and aspect ratio, provision of a database of pore geometry, attenuation of uncertainty in pore type characterization and improvement of rock physics modelling in the absence of reliable Swave velocity data [81].

5. Definition of pore network modeling

PNMs are used in the process of mapping the pore space onto a distinct network of pores and throats connected with the pores. It is possible to calculate the flow rate via the pore openings by first solving the Poiseuille equations and then applying the mass balance equations to each individual pore [25]. Drainage, imbibition, and studies of both single and relative permeability in porous media have all benefited from using these models.

Innumerable other fields of study, in addition to the oil and gas industry [82-84], geology [72, 85, 86], filtration [87, 88], and fuel cells [89], have made use of pore network models in recent years. It is used to make predictions about the macroscopic petrophysical and transport characteristics of porous media, such as porosity, permeability, penetration, diffusivity, forming resistivity factor, capillary pressure breakthrough, and coefficient of thermal expansion. In addition, pore network modeling is capable of accurately recreating the minute flow dynamics that occur inside the pores. Multiphase flow, wettability, capillary trapping, dissolution, diffusion, and convection are some of the other processes that fall within this category. It is crucial to carefully recreate the structure of a pore network that was designed specifically for a certain porous media, right down to the distribution of pore and throat sizes. The development of a pore network model may use statistical techniques, methods based on the process, or methods based on images. Statistical approaches are used to produce random hole and throat sizes with specified connectivities that match quantifiable statistical criteria such as porosity and pore size distribution [90-92]. These methods are used to generate random hole and throat sizes. Statistical approaches will often need core-plane photos as a source from which to generate potentially helpful statistical information on the expansion of a network. In spite of the fact that statistical methods may build pore networks with identical statistical features, the pore morphology of the networks that are formed might be different from that of the sample that was used in the first place (compared with 3-D tomographic pictures [19, 69]). (contrast to images obtained by tomography in three dimensions [86]). Tomographic characteristics derived from two-dimensional computed tomography (CT) scans of critical rock-formation processes, such as sedimentation, compression, carbonation, and diagenesis, are used in process-based techniques. Although process-based approaches provide valuable insight into the influence of geological processes on pore formation, there is a possibility that these approaches will underestimate the degree to which pores are connected to one another, as well as the transport parameters associated with this connectivity [19]. In addition, it may be challenging to recreate varied and diagenetic rocks, such as those found in underground oil deposits. These rocks may be found in places with much oil.

Models of pore networks may be built using a variety of methods. However, imaging techniques (including SEM, TEM, X-ray micro-CT scan, and FIB) and network extraction algorithms [93, 94] are the most used approaches. After image processing, numerical methods such as medial axis (skeletonizing) [95, 96], watershed segmentation [97-100], and maximum ball [101] have proven useful in extracting pore networks. Many scientists have also turned to gas adsorption and mercury intrusion porosimetry to determine pore size distribution experimentally [102]. In pore network modeling, imaging and gas adsorption are the most used techniques for determining pore size distribution [30].

There are three main parts to pore-scale modeling, which describe the geometry and structure of the porous media, (ii) specify and solve the governing equations, and (iii) choose the macroscopic properties [78]. This makes it possible to make use of the benefits of the porous medium, which are often overlooked at larger scales. Pore-scale modeling may be used to estimate the values of dynamic properties like pore networks, which also discretizes the porous structure by heterogeneously spreading voids containing fluid phases. M. Blunt and coworkers [40, 72, 103-107] provide an in-depth discussion of the several fields of study that contribute to characterizing the desired phenomena when modeling pore networks. Blunt has done substantial work on the use of imaging techniques and 3D reconstructions in porous media. These reconstructions and their connections to mathematical models have been used to investigate Newtonian and non-Newtonian flow in a wide variety of rock materials by researchers including Okabe and Blunt (2004), Valvatne et al. (2005), Mostaghimi et al. (2012), and Blunt et al. (2013).

5.1. Different pore types in carbonate rocks (e.g., stiff, fracture, interparticle) and the performance of each pore type modeling in Digital Rock Physics

The rock physics model introduced by Sun (2000) is a dynamic theory of fractured porous media that considers different pore types, including primary or interparticle pores and secondary pores such as vuggy and stiff/crack pores, in carbonate rocks. This model quantifies the effect of pore structure changes on sonic wave velocity and permeability in carbonate rocks by using a frame flexibility factor (g). The factor helps classify different porosity-velocity and porosity-permeability trends with clear geologic interpretation. Accurate imaging and digitization of pore spaces is essential, but it can be challenging due to limitations in imaging techniques. Different imaging techniques covering various length scales, such as X-ray computed tomography (CT) and scanning electron microscopy (SEM), can be combined to improve the accuracy of digital twin creation. The rock physics model introduced by Sun (2000) has been successful in quantifying pore structure and can be used for carbonate reservoir permeability inversion from seismic data. The paper reports on porosity and pore structure parameter inversion from core measurements and well logging for the studied reservoir and its implications for seismic inversion. Carbonate rocks can have various pore types, including primary or interparticle pores and secondary pores such as vuggy and stiff/crack pores [108]. Modeling these different pore types is crucial for understanding fluid flow and transport in porous rocks using Digital Rock Physics (DRP) techniques. The accuracy of imaging and digitization of pore spaces is essential, but it can be challenging due to limitations in imaging techniques [109]. Different imaging techniques covering various length scales, such as X-ray computed tomography (CT) and scanning electron microscopy (SEM), can be combined to improve the accuracy of digital twin creation. However, harmonizing data from imaging and non-imaging techniques can also be challenging [110]. To model different pore types rigorously in DRP simulations, various models have

been proposed, including poro elasticity models such as the one introduced by Sun (2000) [110]. Accurate modeling of each pore type's performance can help improve the understanding of fluid flow and transport in carbonate rocks, leading to better oil and gas recovery.

5.2. Pore Network Modeling related to different rock types (e.g., shale, sandstone, and igneous rocks)

Pore Network Modeling (PNM) is a computational technique used to study fluid flow and transport phenomena in porous media at the microscopic level. It involves constructing a virtual representation of the pore space within a rock sample and simulating fluid flow through the interconnected pores. PNM has been extensively employed to investigate the pore-scale characteristics and fluid flow behavior in different rock types, including shale, sandstone, and igneous rocks [111].

Shale: Shale is a type of fine-grained sedimentary rock characterized by low permeability. PNM is particularly useful in understanding the complex pore network within shale formations. Shale samples often contain a combination of organic matter, clay minerals, and microfractures, which significantly influence fluid flow behavior. By simulating fluid flow through the pore network of shale, PNM helps researchers evaluate the transport properties, such as permeability and diffusivity, and assess the efficiency of shale gas or oil recovery techniques. It also aids in studying the interactions between fluids and organic matter/clay minerals, providing insights into the mechanisms governing fluid storage and release in shale reservoirs [112].

Sandstone: Sandstone is a common sedimentary rock composed of sand-sized grains. PNM allows for the characterization of the pore structure and connectivity within sandstone samples. By simulating fluid flow through the pore network, PNM helps quantify the permeability and hydraulic conductivity of sandstone, which are crucial properties for understanding the behavior of hydrocarbon reservoirs and groundwater aquifers. PNM can also assist in studying the effects of diagenesis, cementation, and compaction on the pore structure of sandstone and their implications for fluid flow [113, 114].

Igneous Rocks: Igneous rocks are formed from the solidification of molten magma or lava. While their overall porosity and permeability are generally lower compared to sedimentary rocks, certain types of igneous rocks can have secondary pores, fractures, or vesicles that contribute to fluid flow. PNM enables the modeling and analysis of the pore network within these features. By simulating fluid flow through the interconnected pores or fractures, PNM helps in understanding the transport properties, such as permeability and flow pathways, within igneous rocks. This information is valuable for studying geothermal systems, volcanic processes, and the potential for fluid migration within igneous formations [115].

6. Open PNM

Over the last twenty years, there has been a significant rise in the number of people interested in EOR models that use pore networks. This can generally be attributed to two primary factors: advancements in computational power and new methods for describing rock-fluid systems in their entirety. Both of these factors have been making significant strides in recent years. With the appropriate physical numerical solution, it is possible that some of the predicted EOR processes, such as a change in wettability in rock-fluid systems, may be recorded by the pore size. Bolandtaba and Skauge (2011) conducted research on the topic of residual oil mobilization by polymer injection. They developed a network to analyze this process while taking into account adsorption particles, polymer

confinement, and viscous forces [116]. This research was published in the journal Energy and Environmental Science. Both Hammond and Unsal (2012) and Qin and Hassanizadeh (2015) investigated methods for microbially enhanced oil recovery [117, 118]. These methods involved surfactants in the rock-fluid system that mobilized oil and altered wettability [119]. Hammond and Unsal (2012) and Qin and Hassanizadeh (2015) looked at these methods. Lu and Yortsos (2001) created a model to simulate in situ forward filtration combustions to investigate the impact of porous microstructure and solid fuel redistribution on filtering combustion dynamics [120]. This model was developed to simulate in situ forward filtration combustions [121].

Xu et al. (2018) investigated the physicochemical and thermal phenomena that occur at combustion fronts [94] to find ways to reduce the risks associated with high combustion temperatures and low oxygen rates in applications that take place in the real world. Sorbie and Collins (2010) included a helpful semi-quantitative explanation in their discussion of the LSWF issue [95]. This explanation was based on theoretical considerations that were made at the pore size. After this, Watson et al. (2011) conducted an uncertainty assessment on wettability change, which is one of the LSWF processes that has received the most attention from researchers. Because of how the network was designed, important oil-water-rock characteristics may now be explored methodically. The authors Boujelben et al. (2018) developed a dynamic model to investigate the effect that LSWF has on oil recovery when the dynamic flow is present. Throughout the course of the recovery process, the spatial distribution of salinity is continuously monitored, and fluid distribution is adjusted so that there is an equilibrium between the forces exerted by capillary action and viscous force. In addition, capillary effects are connected to salinity via the correlation between the contact angle and the concentration of locally injected water [122]. The present research status that uses the PNM approach to describe flow in porous media is outlined in Table 1, which can be found here [123].

The University of Waterloo's Porous Materials Engineering and Analysis Lab created OpenPNM [174], an open-source software suite. It paves the way for modeling porous-material transport in single- and multi-phase scenarios. OpenPNM has been used extensively by academics in their research. Using OpenPNM, Yang et al. [175] simulated shale oil on a pore scale, taking slippage and adsorption into consideration. To study how the geometry of dissolved carbonate rock changes, Esteves et al. [176] employed OpenPNM. The pore network model (PNM), one of the easiest-to-implement systems for studying fluid motion and transport, was among the several pore-scale modeling techniques thoroughly examined by Golparvar et al. [177]. Continued usage of PNM in reactive transport [78] and gas diffusion layers [178] shows no signs of slowing down [73]. PNM is, at its core, a mapping from the intricate pore space continuum to a regular or irregular lattice of sites and bonds. PNM is unique because it can model complex systems and run simulations repeatedly without breaking the bank. To model the movement of sandstone, Fatt [179] constructed four types of 2D networks using varying x and y coordinates. Using Fatt's PNM, Chatzis and Dullien [35] modeled mercury intrusion in sandstones in three dimensions. To extract PNM from core samples, Dong and Blunt [9] used the maximum ball algorithm, a standard method. The PNM characteristics of high-temperature heat-treated sandstones were studied by Mahanta et al. [180]. Using PNM, Foroozesh et al. [181] investigated shale stress-dependent fluid dynamics. From Mehmani et al. [182]'s review of PNM's 60-year history, we discovered that the technique is often used for the study of intricate pore structures, such as the retrieval of PNM from core samples or the production of stochastic PNM with a predetermined porosity and pore coordination number (PCN).

Table 1. An overview of PNM simulation of porous media topic in recent years

Researcher (s)	Pore network modeling simulation topic	Reference (s)
Valvatne et al.	Predictive pore-scale modeling of multiphase flow	[104, 124]
Lopez et al. & Sochi	Simulation of non-Newtonian flow	[125-127] & [128-130]
Al-Gharbi et al.	2-D Simulation of Dynamic pore network modeling	[131]
Behbahani et al. & Li et al.	Simulation of imbibition	[132, 133] & [134]
Chaouche et al.	Simulation of drainage	[135]
Okabe et al.	3-D pore network evolution in carbonate reservoir	[136, 137]
Piri et al. & Hui et al. & Suicmez et al.	Modeling of three-phase flow	[138-141] & [142, 143] & [144-146]
Rhodes et al. & Bijeljic et al.	Simulation of flow in heterogeneous porous media	[147, 148] & [149, 150]
Lu & Hughes and Blunt	Simulation of flow in fractured reservoirs	[151] & [152]
Talabi et al.	Pore-scale simulation of NMR response	[153, 154]
Idowu et al.	Modeling of Rate Effects in Water flooding	[155, 156]
Bekri et al. & Ioannidis and Chatzis	Simulation of carbonate reservoirs and dual-porosity rocks	[157, 158] & [159]
Bustos et al.	Modeling of gas and condensate flow	[160]
Kharabaf et al. & Chen et al. & Romero-Zeron	Mobilization of foams in porous media	[161, 162] & [163]
Hammond et al.	Modeling of oil displacement by wettability-altering surfactant solution	[117]
Ma et al.	Simulation of non-ideal gas flow in micro-and nano-porous materials	[164]
Wang et al.	Modeling of Permeability of porous media containing methane hydrate	[165, 166]
Aghabozorgi and Rostami	investigation of polymer adsorption in porous media	[167]
Huang et al. & Wang et al.	Modeling of two-phase shale matrix flows	[168] & [169]
Tansey et al.	Modeling of reactive transport and dissolution in porous media	[170]
Zhan et al. & Feng et al.	Migration model of fine particles	[171] & [172]
Seetha et al.	Modeling of nanoparticle transport in porous media	[173]
Boujelben et al.	Modeling of low salinity water injection	[123]

7. Limitations, uncertainties, and potential pitfalls

Digital Rock Physics (DRP), which encompasses techniques like Pore Network Modeling (PNM), offers several advantages for studying rock properties and fluid flow behavior. However, it is important to consider the limitations, uncertainties, and potential pitfalls associated with DRP when comparing it to conventional methods. Here are some key points to consider:

7.1. Representativeness of pore-scale models

The accuracy of DRP techniques heavily relies on the representation of the pore space within the virtual models. Constructing pore-scale models involves interpreting imaging data or making assumptions about the rock's structure and properties. If the imaging data is limited or does not adequately capture the intricate details of the pore network, the resulting models may not be representative of the actual rock sample. This can introduce uncertainties and impact the reliability of the calculated properties and flow behavior [183].

7.2. Spatial resolution

The spatial resolution of the imaging data used to construct the pore-scale models is critical. Insufficient resolution may not capture the fine-scale features of the pore network accurately, leading to an incomplete representation of the rock's complexity. Consequently, the calculated properties and flow behavior may deviate from reality. Obtaining high-resolution imaging data can be challenging and may require advanced imaging techniques, which may not always be readily available [184].

7.3. Computational complexity

DRP simulations, such as Pore Network Modeling (PNM), can be computationally demanding. Large-scale simulations or complex rock geometries can require significant computational resources and time. Conducting extensive parameter studies or simulating large volumes of rock samples may be impractical due to these computational limitations. Researchers must carefully consider the trade-off between computational feasibility and desired accuracy [185].

7.4. Assumptions and simplifications

DRP techniques often rely on assumptions and simplifications to model the pore network and fluid-rock interactions. These assumptions may include assumptions about pore shapes, connectivity, and fluid-rock interactions. While these simplifications facilitate computational efficiency, they can introduce uncertainties and potential biases in the results. It is crucial to validate these assumptions against experimental data or alternative modeling approaches whenever possible [183].

7.5. Fluid-fluid and fluid-rock interactions

DRP techniques primarily focus on single-phase fluid flow, neglecting the complexities of multiphase flow and the interactions between different fluids and the rock matrix. Multiphase flow phenomena, such as capillary effects or phase behavior, can significantly impact fluid flow behavior and rock properties. Extending DRP techniques to accurately model multiphase flow remains an active area of research, and current approaches may not fully capture these complexities [186].

7.6. Validation and calibration

Validating and calibrating DRP results against experimental measurements is crucial to assess their reliability. However, obtaining experimental data that closely matches the conditions and properties of the DRP simulations can be challenging. Differences between experimental and simulated results can arise due to various factors, including measurement uncertainties, sample heterogeneity, and boundary effects. It is essential to critically analyze and interpret the agreement between DRP results and experimental data, understanding the potential sources of discrepancies [187].

7.7. Applicability to heterogeneous rocks

Highly heterogeneous rocks, characterized by significant spatial variations in properties or the presence of localized features such as fractures, vugs, or grain size variations, can pose challenges for DRP techniques. Representing these complexities in pore-scale models and accurately simulating their impact on fluid flow behavior can be difficult. The simplified representation of heterogeneities may limit the applicability and accuracy of DRP in such cases [188].

7.8. Data availability and accessibility

The availability of high-quality imaging data required for DRP techniques may be limited, especially for certain rock types or specific research or industrial settings. Access to advanced imaging technologies, such as high-resolution

micro-CT scanners, may be restricted or not widely accessible. Limited data availability can restrict the widespread application of DRP and pose challenges for researchers seeking to utilize these techniques [6]. Considering these limitations and potential pitfalls, it is important to use DRP techniques judiciously, supplementing the findings with conventional methods whenever possible.

8. Various approaches in reconstruction and reaching to pore scale

There have been several recent advances in modeling strategies for simulating pore structures. These include the optimization-based algorithm (OBA), the multiple-point-statistics procedure, the process-oriented pore-scale approach, and hybrid approaches [27].

This maximal sphere (or ball) was developed by Silin and Patzek [34] to evaluate the pore space geometry and connectivity in sedimentary rocks. They established a link between the pore bodies and the cervical ganglia, which had previously been disconnected. Al-Kharusi and Blunt [30] extracted networks using the maximum sphere technique and compared the findings to those obtained with other approaches. Instead of systematically constructing a vacuum ball, they employed a searching strategy to define it. Because of this, less RAM is now accessible. Segmentation affects macroscopic property estimates, CT-image quality, and the digital volume utilized for extraction and simulations, although the image-based pore network model helps obtain pore morphology and comprehend transport in porous materials. Another factor limiting the method's widespread use is unreliable X-ray imaging resources [35].

For those who don't have access to X-ray imaging technology, statistical reconstruction approaches provide a viable alternative method of building pore networks [189]. Using a normal or Weibull distribution for randomly generated pore sizes, this method adjusts the geometric properties of a typical network model such that it is consistent with the most relevant experimental data. In addition to predicting the properties as mentioned above [12, 190], the constructed network models may be utilized to predict additional, more nebulous characteristics. Fischer and Celia [190] reliably predicted absolute and relative permeability for a wide range of rocks by calibrating a network model to the capillary pressure measurements. Dillard et al. [191] used a network model similarly, adjusting it to capillary pressure so that it could predict the outcomes of dissolving tests. However, selecting the initial estimate values of the network parameters is a vital and challenging step, even if these building methodologies have been utilized to develop random pore networks that match some flow patterns and anticipate others. One must understand the porous medium and its unique pore size distribution to do this task successfully. Assuming you have a good idea of the network's parameters, you can speed up the building process by reducing the number of rounds.

Several techniques have been used to categorize PNM extraction procedures, with the most prevalent distinguishing two overarching classes: topology-central and morphology-central approaches [183]. Some of the most well-known methods in both categories—the medial axis and maximum balls algorithms, as well as the watershed algorithm—will be covered in the following sections. The medial axis separation method is connected to other procedures based on skeletonization, which has a common core topology. These methods all use a thinning effect, which shrinks the pore space of rocks until a medial axis, a thin line marking pore space centers, becomes visible. Though there may be difficulties with pore identification and pore body partitioning, thin films are often fabricated by beginning at the big pores, which adequately portrays pore connectivity. Potentially problematic for skeletonization-based approaches is their extreme sensitivity to imperfections in the input pore space, which may result in widespread pore over-

segmentation when several fake brunches are detected. It's possible to avoid this issue by preprocessing the raw photos [32, 95]. When modeling pore networks, Silin and Patzek [34] proposed using a maximum ball (MB) technique. The most extensive inscribed spheres, with centers on each empty voxel contacting the grain or a boundary, are then excised, yielding the maximum balls. Removing spheres that are entirely enclosed within other spheres is the next stage in simplifying the output. Then, those people may be grouped into families, with each family's progenitor functioning as a pore. As a result, a throat might have two unrelated parents [34]. The maximal ball algorithm relies heavily on a differentiation method known as explicit pore and throat differentiation. Despite the MB method's success in locating pores, it may be challenging to create throats owing to the plethora of alternatives for joining holes via the overlap of smaller spheres [35]. Lip sizes generated by MB networks were shown to be significantly reduced compared to those generated by traditional approaches [192].

The watershed approach was developed over a century ago by Sheppard et al. [193] and Thompson et al. [194], allowing the pore space to be separated into individual nodes of the network. It may be used for the distance map derived from the picture of the pore spaces after partitioning them. Throats act as the cellular walls that divide each pore in this model [195]. For optimal results on pictures with variable minima and catchment basins, watershed segmentation combined two widely used image processing algorithms: distance and watershed transformations. To see how this method works, picture two interconnected objects with their centers at their respective local deepest points (they call catchment basins). The first line of contact between two such "valleys" or "peaks" that water reaches is known as a watershed ridge line. You can tell which parts are pore bodies and which are pore throats by slicing the material in half along this line [195]. Watershed segmentation is susceptible to noise and has a general propensity to over-segment input images since any local minimum might quickly become the catchment basin.

It has been noted by Gostick [192] that the distance transform may exhibit ridges and plateaus, which are generally considered local maxima, and peaks in the centers of individual pores. Sub-Network of an Over-segmented Watershed (SNOW) is an improved algorithm that finds over-segmentation and the false local maxima that cause it. More information on this strategy is provided below.

9. Pore network modeling of imbibition in rocks using imaging-based method

Near-static approximations are often used to depict the gradual penetration of a wetting fluid in porous materials at the pore size. Basic pore-filling principles are used to approximate capillary forces. Predictions of imbibition relative permeability are notoriously unreliable; hence the method is controversial in the academic community. The correctness of a model is often evaluated by contrasting it with results from large-scale investigations. That's why we've explored why it's so hard to generalize the model's performance and why a quasi-static description isn't beneficial. The authors of this paper, Bultreys et al. [196], investigate whether such a model can reliably predict the fluid distributions at the pore size responsible for the observed behavior at the continuum scale. Using data on the development of fluid arrangements obtained from rapid synchrotron micro-CT scans, they evaluate a complex model for cooperative pore filling against quasi-static simulations, which include capillary-dominated pore filling and snap-off for two kinds of rocks. Fig. 5 depicts their suggested procedure for validating pore-scale models of multi-phase flow. After the pore network model was extracted from the micro-CT scan of the sample, numerical simulation or experimental micro-CT imaging was used to construct a series of fluid distributions inside the pore network model.

The next step is to determine whether the up-scaled flow parameters and vacancy fill rates predicted by the simulation are comparable to those seen in the experiment.

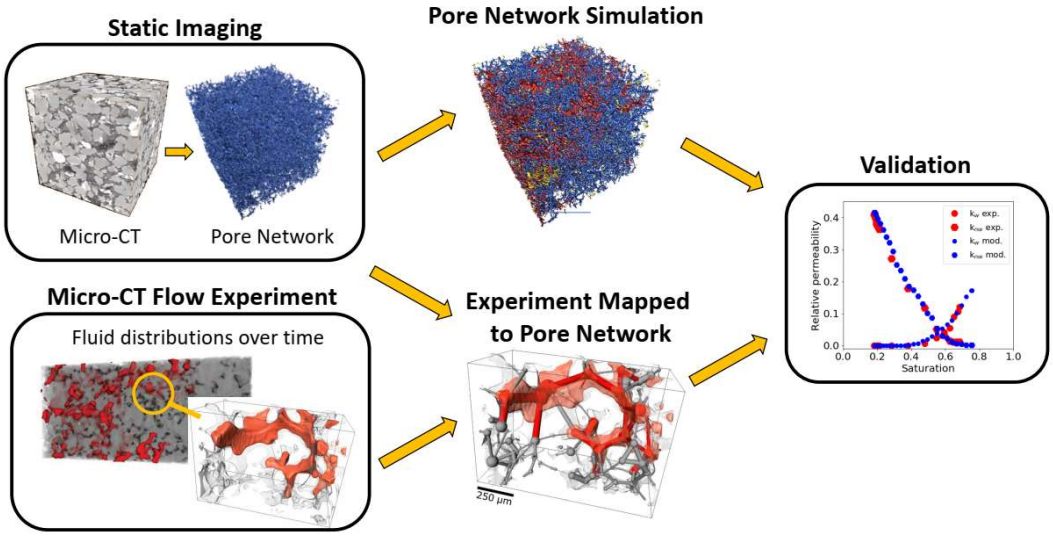


Fig. 5. The workflow for validation of pore scale multi-phase flow models for imbibition in rocks proposed by Bultreys et al. (The workflow for validation of pore-scale multiphase flow models proposed in this paper. After extracting a pore network model from a micro-CT scan of the sample, we generated a series of fluid distributions in the pore network model by either numerical simulation (independent of flow experiments) or experimental micro-CT imaging. We then investigate whether the simulation succeeds at filling pores in approximately the right order compared to the experiment, particularly with regard to predicting upscaled flow properties.) [196]

Despite decades of research, quasi-static PNMs have not been proven to have adequate general prediction abilities [197]. However, some early research indicated that these models' projected relative permeability curves could really match experimental data under certain conditions [20, 198]. Doubts about the extracted network, the pore-filling criteria, and the adequacy of a quasi-static description have all been cited as potential causes for alarm. Recent rapid time-resolved X-ray micro-CT investigations [199, 200] have discovered evidence of viscosity and inertial effects such as ganglion dynamics and intermittency, calling into question the quasi-static assumption. In rock samples, the approximation does not match up with experiments, but whether this means the quasi-static approximation makes fundamentally wrong predictions at the intermediate size of the fluid clusters is unclear. Simplifying a model increases the difficulty of its validation since it introduces numerous internal microscopic degrees of freedom while producing a few macroscopic parts. Overfitting the model to the reported experimental values of continuum scale flow parameters such as relative permeability and capillary pressure-saturation curves [201, 202] is thus conceivable. Instead, we need granular criteria that allow the recovery of critical aspects of the system's internal state [203].

10. Conclusion

Fluid flow through a porous material is highly dependent on the structure and geometry of its pores. Pore size and shape are influenced by the distribution and orientation of solid particles. Several petrophysical properties and transport processes, such as solid mechanics, acoustics, electricity, fluid transport, and fluid-solid interaction, can be studied with the help of digital core management in rock petrophysics modeling. However, an accurate three-

dimensional digital rock model is the end result of any numerical modeling. Phase exchange, non-Newtonian displacement, non-Darcy flow, reactive transport, and thermodynamically consistent oil layers are just some of the many physical and chemical phenomena that have been successfully modeled using pore network representations. In this post, we take a quick look at the various approaches to creating pore networks. The subject at hand is how to integrate information about pore systems that have been determined experimentally. Current applications to pore, network models, are discussed, as well as the effects of adsorption, dissolution, and precipitation on transport coefficients and biomass growth. Although other methods are more precise, pore network models have been shown to help understand and predict mesoscale phenomena by the engineering community, which typically uses homogenized continuous porous media. An overview of how digital rock has evolved from its origins in porous media research to its development into a practical tool Digital rock analysis analyzes rock samples at the pore scale, utilizing X-ray micro-computed tomography and pore-scale modeling. Digital rock is discussed in the petroleum industry and its applications in reservoir characterization, fluid flow simulation, and enhanced oil recovery. A review of digital rock is presented, emphasizing the importance of working with complementary laboratory techniques and carefully interpreting the results. It also discussed how pore network modeling can be used to simulate fluid flow in porous media. Digital rocks will be integrated with other data sources in the future, including new imaging and modeling techniques.

Nomenclature

Abbreviations		**Symbols**	
XRD	X-ray diffraction	A	Cross-section area
UV-VIS	Ultraviolet-visible light spectrometer	L	Length of sample
FT-IR	Fourier Transform Infrared Spectroscopy	k, kabs	Absolute permeability
SARA	Saturates, Aromatics, Resins, Asphaltenes	Kr	Relative Permeability
CMC	Critical Micelle Concentration	Pc	Capillary Pressure
EOR	Enhanced Oil Recovery	θ	Contact Angle
FW	Formation Water	σ	Interfacial tension (IFT)
SW	Sea Water	Ø	Porosity
LSWI	Low Salinity Water Injection	ΔP	Pressure drops across the core
TDS	Total Dissolved Solids	Si	Saturates of phase i
PV	Pore Volume	T	Time

References

[1] Sahimi, M., 1993. Flow phenomena in rocks: from continuum models to fractals, percolation, cellular automata, and simulated annealing, Reviews of Modern Physics, 65(4), 1393. ttps://doi.org/10.1103/RevModPhys.65.1393
[2] Trogadas, P., Ramani, V., Strasser, P., Fuller, T. F., Coppens, M. O., 2016. Hierarchically structured nanomaterials for electrochemical energy conversion, Angewandte Chemie International Edition, 55(1), 122-148. https://doi.org/10.1002/anie.201506394
[3] Jackson, E. A., Hillmyer, M. A., 2010. Nanoporous membranes derived from block copolymers: from drug delivery to water filtration, ACS Nano, 4(7), 3548-3553. https://doi.org/10.1021/nn1014006
[4] De Jong, J., Lammertink, R. G., Wessling, M., 2006. Membranes and microfluidics: a review, Lab on a Chip, 6(9), 1125-1139. https://doi.org/10.1039/B603275C
[5] Velev, O. D., Lenhoff, A. M., 2000. Colloidal crystals as templates for porous materials, Current Opinion in Colloid & Interface Science, 5(1-2), 56-63. https://doi.org/10.1016/S1359-0294(00)00039-X

[6] Wildenschild, D., Sheppard, A. P., 2013. X-ray imaging and analysis techniques for quantifying pore-scale structure and processes in subsurface porous medium systems, Advances in Water Resources, 51, 217-246. https://doi.org/10.1016/j.advwatres.2012.07.018
[7] Andisheh-Tadbir, M., Orfino, F. P., Kjeang, E., 2016. Three-dimensional phase segregation of micro-porous layers for fuel cells by nano-scale X-ray computed tomography, Journal of Power Sources, 310, 61-69. https://doi.org/10.1016/j.jpowsour.2016.02.001
[8] Andrä, H., Combaret, N., Dvorkin, J., Glatt, E., Han, J., Kabel, M., Keehm, Y., Krzikalla, F., Lee, M., Madonna, C., Marsh, M., Mukerji, T., Saenger, E.H., Sain, R., Saxena, N., Ricker, S., Wiegmann, A., Zhan, X., 2013. Digital rock physics benchmarks—Part I: Imaging and segmentation, Computers & Geosciences, 50, 25-32. https://doi.org/10.1016/j.cageo.2012.09.005
[9] Chatzis, I., Dullien, F. A., 1977. Modelling pore structure by 2-D and 3-D networks with application to sandstones, Journal of Canadian Petroleum Technology, 16(01). https://doi.org/10.2118/77-01-09
[10] Mohanty, K. K., 1981. Fluids in porous media: two-phase distribution and flow, University of Minnesota.
[11] Celia, M. A., Reeves, P. C., Ferrand, L. A., 1995. Recent advances in pore scale models for multiphase flow in porous media, Reviews of Geophysics, 33(S2), 1049-1057. https://doi.org/ 10.1029/95RG00248
[12] Blunt, M. J., 2001. Flow in porous media—pore-network models and multiphase flow, Current Opinion in Colloid & Interface Science, 6(3), 197-207. https://doi.org/10.1016/S1359-0294(01)00084-X
[13] Primkulov, B.K., Talman, S., Khaleghi, K., Rangriz Shokri, A., Chalaturnyk, R., Zhao, B., MacMinn, C.W., Juanes, R., 2018. Quasistatic fluid-fluid displacement in porous media: Invasion-percolation through a wetting transition, Physical Review Fluids, 3(10), 104001. https://doi.org/10.1103/PhysRevFluids.3.104001
[14] Dong, H., 2007. Micro-CT Imaging and Pore Network Extraction, PhD dissertation, Imperial College, London.
[15] Sahimi, M., 2011. Flow and transport in porous media and fractured rock: from classical methods to modern approaches, John Wiley & Sons.
[16] Bryant, S. L., King, P. R., Mellor, D. W., 1993. Network model evaluation of permeability and spatial correlation in a real random sphere packing, Transport in Porous Media, 11(1), 53-70. https://doi.org/10.1007/BF00614635
[17] Bryant, S. L., Mellor, D. W., Cade, C. A., 1993. Physically representative network models of transport in porous media, AIChE Journal, 39(3), 387-396. https://doi.org/10.1002/aic.690390303
[18] Bryant, S., Blunt, M., 1992. Prediction of relative permeability in simple porous media, Physical Review A, 46(4), 2004. https://doi.org/10.1103/PhysRevA.46.2004
[19] Øren, P.-E., Bakke, S., 2002. Process based reconstruction of sandstones and prediction of transport properties, Transport in Porous Media, 46(2), 311-343. https://doi.org/10.1023/A:1015031122338
[20] Øren, P.-E., Bakke, S., Arntzen, O. J., 1998. Extending predictive capabilities to network models, SPE Journal, 3(04), 324-336. https://doi.org/10.2118/52052-PA
[21] Manchanda, R., Olson, J. E., Sharma, M. M., 2012. Permeability anisotropy and dilation due to shear failure in poorly consolidated sands, in SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, USA. https://doi.org/10.2118/152432-MS
[22] Liu, Y., Zhou, X., You, Z., Yao, S., Gong, F., Wang, H., 2017. Discrete element modeling of realistic particle shapes in stone-based mixtures through MATLAB-based imaging process, Construction and Building Materials, 143, 169-178. https://doi.org/10.1016/j.conbuildmat.2017.03.037
[23] Raziperchikolaee, S., Alvarado, V., Yin, S., 2014. Microscale modeling of fluid flow-geomechanics-seismicity: Relationship between permeability and seismic source response in deformed rock joints, Journal of Geophysical Research: Solid Earth, 119(9), 6958-6975. https://doi.org/10.1002/2013JB010758
[24] Yang, Z., Juanes, R., 2018. Two sides of a fault: Grain-scale analysis of pore pressure control on fault slip, Physical Review E, 97(2), 022906. https://doi.org/10.1103/PhysRevE.97.022906
[25] Bhattad, P., Willson, C. S., Thompson, K. E., 2011. Effect of network structure on characterization and flow modeling using X-ray micro-tomography images of granular and fibrous porous media, Transport in Porous Media, 90(2), 363-391. https://doi.org/10.1007/s11242-011-9789-7
[26] Blunt, M. J., 2017. Multiphase flow in permeable media: A pore-scale perspective, Cambridge University Press.
[27] Sadeghnejad, S., Gostick, J., 2020. Multiscale reconstruction of vuggy carbonates by pore-network modeling and image-based technique, SPE Journal, 25(01), 253-267. https://doi.org/10.2118/198902-PA
[28] Sun, Q., Zhang, N., Fadlelmula, M., Wang, Y., 2018. Structural regeneration of fracture-vug network in naturally fractured vuggy reservoirs, Journal of Petroleum Science and Engineering, 165, 28-41. https://doi.org/10.1016/j.petrol.2017.11.030
[29] Beg, M. S., 2022. Multiscale Pore Network Modeling of Hierarchical Media with Applications to Improved Oil and Gas Recovery, University of Waterloo.
[30] Al-Kharusi, A. S., Blunt, M. J., 2007. Network extraction from sandstone and carbonate pore space images, Journal of Petroleum Science and Engineering, 56(4), 219-231. https://doi.org/10.1016/j.petrol.2006.09.003
[31] Prodanović, M., Mehmani, A., Sheppard, A. P., 2015. Image-based multiscale network modelling of microporosity in carbonates, Geological Society, London, Special Publications, 406(1), 95-113. https://doi.org/10.1144/SP406.9
[32] Lindquist, W. B., Lee, S. M., Coker, D. A., Jones, K. W., Spanne, P., 1996. Medial axis analysis of void structure in three-dimensional tomographic images of porous media, Journal of Geophysical Research: Solid Earth, 101(B4), 8297-8310. https://doi.org/10.1029/95JB03039
[33] Sarker, M., Siddiqui, S., 2009. Advances in micro-CT based evaluation of reservoir rocks, in SPE Saudi Arabia Section Technical Symposium, Al-Khobar, Saudi Arabia. https://doi.org/10.2118/126039-MS

[34] Silin, D., Patzek, T., 2006. Pore space morphology analysis using maximal inscribed spheres, Physica A: Statistical Mechanics and its Applications, 371(2), 336-360. https://doi.org/10.1016/j.physa.2006.04.048
[35] Dong, H., Blunt, M. J., 2009. Pore-network extraction from micro-computerized-tomography images, Physical Review E, 80(3), 036307. https://doi.org/10.1103/PhysRevE.80.036307
[36] Mahabadi, N., Dai, S., Seol, Y., Sup Yun, T., Jang, J., 2016. The water retention curve and relative permeability for gas production from hydrate-bearing sediments: pore-network model simulation, Geochemistry, Geophysics, Geosystems, 17(8), 3099-3110. https://doi.org/10.1002/2016GC006372
[37] Merey, Ş., 2019. Prediction of transport properties for the Eastern Mediterranean Sea shallow sediments by pore network modelling, Journal of Petroleum Science and Engineering, 176, 403-420. https://doi.org/10.1016/j.petrol.2019.01.081
[38] Chauhan, S., Rühaak, W., Khan, F., Enzmann, F., Mielke, P., Kersten, M., Sass, I., 2016. Processing of rock core microtomography images: Using seven different machine learning algorithms, Computers & Geosciences, 86, 120-128. https://doi.org/10.1016/j.cageo.2015.10.013
[39] Koroteev, D. A., Nadeev, A. N., Yakimchuk, I. V., Varfolomeev, I. A., 2017. Method for building a 3D model of a rock sample, Google Patents. https:// https://patents.google.com/patent/US9558588B2/en
[40] Blunt, M.J., Bijeljic, B., Dong, H., Gharbi, O., Iglauer, S., Mostaghimi, P., Paluszny, A., Pentland, C., 2013. Pore-scale imaging and modelling, Advances in Water Resources, 51, 197-216. https://doi.org/10.1016/j.advwatres.2012.03.003
[41] Koroteev, D.; Dinariev, O.; Evseev, N.; Klemin, D.; Nadeev, A.; Safonov, S.; Gurpinar, O.; Berg, S.; van Kruijsdijk, C.; Armstrong, R.; Myers, M.T.; Hathon, L.; de Jong, H., 2014. Direct hydrodynamic simulation of multiphase flow in porous rock, Petrophysics-The SPWLA Journal of Formation Evaluation and Reservoir Description, 55(04), 294-303.
[42] Berg, C. F., Lopez, O., Berland, H., 2017. Industrial applications of digital rock technology, Journal of Petroleum Science and Engineering, 157, 131-147. https://doi.org/10.1016/j.petrol.2017.06.074
[43] Evseev, N., Dinariev, O., Hurlimann, M., Safonov, S., 2015. Coupling multiphase hydrodynamic and NMR pore-scale modeling for advanced characterization of saturated rocks, Petrophysics-The SPWLA Journal of Formation Evaluation and Reservoir Description, 56(01), 32-44.
[44] Koroteev, D., Dinariev, O., Evseev, N., Klemin, D., Safonov, S., Gurpinar, O., Berg, S., van Kruijsdijk, C., Myers, M., Hathon, L., de Jong, H., Armstrong, R., 2013. Application of digital rock technology for chemical EOR screening, in SPE Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia. https://doi.org/10.2118/165258-MS
[45] Klemin, D., Nadeev, A., Ziauddin, M., 2015. Digital rock technology for quantitative prediction of acid stimulation efficiency in carbonates, in SPE Annual Technical Conference and Exhibition, Houston, Texas, USA. https://doi.org/10.2118/174807-MS
[46] Yang, Y., Fugui, L., Zhang, Q., Li, Y., Wang, K., Xu, Q., Yang, J., Shang, Z., Junming, L., Wang, J., Liu, Z., Song, H., Sun, W., Li, J., Yao, J., 2023. Recent Advances in Multiscale Digital Rock Reconstruction, Flow Simulation, and Experiments during Shale Gas Production, Energy & Fuels, 37(4), 2475-2497. https://doi.org/10.1021/acs.energyfuels.2c03470
[47] Frank, F., Liu, C., Alpak, F. O., Berg, S., Riviere, B., 2018. Direct numerical simulation of flow on pore-scale images using the phase-field method, SPE Journal, 23(05), 1833-1850. https://doi.org/10.2118/182607-PA
[48] Bultreys, T., Van Hoorebeke, L., Cnudde, V., 2015. Multi-scale, micro-computed tomography-based pore network models to simulate drainage in heterogeneous rocks, Advances in Water Resources, 78, 36-49. https://doi.org/10.1016/j.advwatres.2015.02.003
[49] Liu, M., Mostaghimi, P., 2017. Pore-scale simulation of dissolution-induced variations in rock mechanical properties, International Journal of Heat and Mass Transfer, 111, 842-851. https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.049
[50] Liu, M., Shabaninejad, M., Mostaghimi, P., 2017. Impact of mineralogical heterogeneity on reactive transport modelling, Computers & Geosciences, 104, 12-19. https://doi.org/10.1016/j.cageo.2017.03.020
[51] Yu, X., Regenauer-Lieb, K., Tian, F.-B., 2020. Effects of surface roughness and derivation of scaling laws on gas transport in coal using a fractal-based lattice Boltzmann method, Fuel, 259, 116229. https://doi.org/10.1016/j.fuel.2019.116229
[52] Porter, M. L., Schaap, M. G., Wildenschild, D., 2009. Lattice-Boltzmann simulations of the capillary pressure–saturation–interfacial area relationship for porous media, Advances in Water Resources, 32(11), 1632-1640. https://doi.org/10.1016/j.advwatres.2009.08.009
[53] Yoon, H., Kang, Q., Valocchi, A. J., 2015. Lattice Boltzmann-based approaches for pore-scale reactive transport, Reviews in Mineralogy and Geochemistry, 80(1), 393-431. https://doi.org/10.2138/rmg.2015.80.12
[54] Abdulle, A., Budáč, O., 2016. A reduced basis finite element heterogeneous multiscale method for Stokes flow in porous media, Computer Methods in Applied Mechanics and Engineering, 307, 1-31. https://doi.org/10.1016/j.cma.2016.03.016
[55] Sandström, C., Larsson, F., Runesson, K., Johansson, H., 2013. A two-scale finite element formulation of Stokes flow in porous media, Computer Methods in Applied Mechanics and Engineering, 261, 96-104. https://doi.org/10.1016/j.cma.2013.02.013
[56] Ramstad, T., Idowu, N., Nardi, C., Øren, P.-E., 2012. Relative permeability calculations from two-phase flow simulations directly on digital images of porous rocks, Transport in Porous Media, 94(2), 487-504. https://doi.org/10.1007/s11242-011-9877-8
[57] Boek, E. S., Venturoli, M., 2010. Lattice-Boltzmann studies of fluid flow in porous media with realistic rock geometries, Computers & Mathematics with Applications, 59(7), 2305-2314. https://doi.org/10.1016/j.camwa.2009.08.063
[58] Prodanović, M., Lindquist, W., Seright, R., 2007. 3D image-based characterization of fluid displacement in a Berea core, Advances in Water Resources, 30(2), 214-226. https://doi.org/10.1016/j.advwatres.2005.05.015

[59] Xu, L., Yu, X., Regenauer-Lieb, K., 2020. An immersed boundary-lattice Boltzmann method for gaseous slip flow, Physics of Fluids, 32(1), 012002. https://doi.org/10.1063/1.5126392
[60] Yu, X., Xu, L., Regenauer-Lieb, K., Jing, Y., Tian, F.-B., 2020. Modeling the effects of gas slippage, cleat network topology and scale dependence of gas transport in coal seam gas reservoirs, Fuel, 264, 116715. https://doi.org/10.1016/j.fuel.2019.116715
[61] Liu, M., Mostaghimi, P., 2017. High-resolution pore-scale simulation of dissolution in porous media, Chemical Engineering Science, 161, 360-369. https://doi.org/10.1016/j.ces.2016.12.064
[62] Wang, G., Jiang, C., Shen, J., Han, D., Qin, X., 2019. Deformation and water transport behaviors study of heterogeneous coal using CT-based 3D simulation, International Journal of Coal Geology, 211, 103204. https://doi.org/10.1016/j.coal.2019.05.011
[63] Mahdiabad, O. A., 2020. Primary drainage in static pore network modelling: a comparative study, University of Leoben.
[64] Chung, T., Wang, Y. D., Armstrong, R. T., Mostaghimi, P., 2019. Approximating permeability of microcomputed-tomography images using elliptic flow equations, SPE Journal, 24 (03), 1154-1163. https://doi.org/10.2118/191379-PA
[65] Jiang, Z., Van Dijke, M., Sorbie, K. S., Couples, G. D., 2013. Representation of multiscale heterogeneity via multiscale pore networks, Water Resources Research, 49 (9), 5437-5449. https://doi.org/10.1002/wrcr.20304
[66] Silin, D., Tomutsa, L., Benson, S. M., Patzek, T. W., 2011. Microtomography and pore-scale modeling of two-phase fluid distribution, Transport in Porous Media, 86 (2), 495-515. https://doi.org/10.1007/s11242-010-9636-2
[67] Hinebaugh, J., Fishman, Z., Bazylak, A., 2010. Unstructured pore network modeling with heterogeneous PEMFC GDL porosity distributions, Journal of The Electrochemical Society, 157 (11), B1651. https://doi.org/10.1149/1.3486095
[68] Thiedmann, R., Manke, I., Lehnert, W., Schmidt, V., 2011. Random geometric graphs for modelling the pore space of fibre-based materials, Journal of Materials Science, 46 (24), 7745-7759. https://doi.org/10.1007/s10853-011-5754-7
[69] Ioannidis, M. A., Chatzis, I., 1993. Network modelling of pore structure and transport properties of porous media, Chemical Engineering Science, 48 (5), 951-972. https://doi.org/10.1016/0009-2509(93)80333-L
[70] Hunt, A., 2005. Basic transport properties in natural porous media, Complexity, 10 (1), 22-37. https://doi.org/10.1002/cplx.20067
[71] Rebai, M., Prat, M., 2009. Scale effect and two-phase flow in a thin hydrophobic porous layer. Application to water transport in gas diffusion layers of proton exchange membrane fuel cells, Journal of Power Sources, 192 (2), 534-543. https://doi.org/10.1016/j.jpowsour.2009.02.090
[72] Blunt, M. J., Jackson, M. D., Piri, M., Valvatne, P. H., 2002. Detailed physics, predictive capabilities and macroscopic consequences for pore-network models of multiphase flow, Advances in Water Resources, 25 (8-12), 1069-1089. https://doi.org/10.1016/S0309-1708(02)00049-0
[73] Gostick, J. T., Ioannidis, M. A., Fowler, M. W., Pritzker, M. D., 2007. Pore network modeling of fibrous gas diffusion layers for polymer electrolyte membrane fuel cells, Journal of Power Sources, 173 (1), 277-290. https://doi.org/10.1016/j.jpowsour.2007.04.059
[74] Reeves, P. C., Celia, M. A., 1996. A functional relationship between capillary pressure, saturation, and interfacial area as revealed by a pore-scale network model, Water Resources Research, 32 (8), 2345-2358. https://doi.org/10.1029/96WR01105
[75] Joekar-Niasar, V., Hassanizadeh, S., 2012. Analysis of fundamentals of two-phase flow in porous media using dynamic pore-network models: A review, Critical Reviews in Environmental Science and Technology, 42 (18), 1895-1976. https://doi.org/10.1080/10643389.2011.574101
[76] Encalada, Á., Barzola-Monteses, J., Espinoza-Andaluz, M., 2020. A Permeability–Throat Diameter Correlation for a Medium Generated with Delaunay Tessellation and Voronoi Algorithm, Transport in Porous Media, 132 (1), 201-217. https://doi.org/10.1007/s11242-020-01387-z
[77] Johnson, A., Roy, I., Matthews, G., Patel, D., 2003. An improved simulation of void structure, water retention and hydraulic conductivity in soil with the Pore-Cor three-dimensional network, European Journal of Soil Science, 54 (3), 477-490. https://doi.org/10.1046/j.1365-2389.2003.00504.x
[78] Raoof, A., Nick, H. M., Hassanizadeh, S. M., Spiers, C., 2013. PoreFlow: A complex pore-network model for simulation of reactive transport in variably saturated porous media, Computers & Geosciences, 61, 160-174. https://doi.org/10.1016/j.cageo.2013.08.005
[79] Bui, J. C., Lees, E. W., Pant, L. M., Zenyuk, I. V., Bell, A. T., Weber, A. Z., 2022. Continuum Modeling of Porous Electrodes for Electrochemical Synthesis, Chemical Reviews. https://doi.org/10.1021/acs.chemrev.1c00901
[80] Ghiasi-Freez, J., Soleimanpour, I., Kadkhodaie-Ilkhchi, A., Ziaii, M., Sedighi, M., Hatampour, A., 2012. Semi-automated porosity identification from thin section images using image analysis and intelligent discriminant classifiers, Computers & Geosciences, 45, 36-45. https://doi.org/10.1016/j.cageo.2012.03.006
[81] Sharifi, J., 2022. Intelligent pore type characterization: Improved theory for rock physics modelling, Geophysical Prospecting, 70 (5), 921-937. https://doi.org/10.1111/1365-2478.13204
[82] Shabani Afrapoli, M., Alipour, S., Torsaeter, O., 2011. Fundamental study of pore scale mechanisms in microbial improved oil recovery processes, Transport in Porous Media, 90(3), 949-964. https://doi.org/10.1007/s11242-011-9825-7
[83] Bondino, I., McDougall, S. R., Hamon, G., 2009. A pore-scale modelling approach to the interpretation of heavy oil pressure depletion experiments, Journal of Petroleum Science and Engineering, 65(1-2), 14-22. https://doi.org/10.1016/j.petrol.2008.12.010
[84] Hou, J., 2007. Network modeling of residual oil displacement after polymer flooding, Journal of Petroleum Science and Engineering, 59 (3-4), 321-332. https://doi.org/10.1016/j.petrol.2007.04.012
[85] Man, H., Jing, X., 2000. Pore network modelling of electrical resistivity and capillary pressure characteristics, Transport in Porous Media, 41 (3), 263-285. https://doi.org/10.1023/A:1006612100346

[86] Øren, P.-E., Bakke, S., 2003. Reconstruction of Berea sandstone and pore-scale modelling of wettability effects, Journal of Petroleum Science and Engineering, 39(3-4), 177-199. https://doi.org/10.1016/S0920-4105(03)00062-7
[87] Gribble, C.M., Matthews, G.P., Laudone, G.M., Turner, A., Ridgway, C.J., Schoelkopf, J., Gane, P.A.C., 2011. Porometry, porosimetry, image analysis and void network modelling in the study of the pore-level properties of filters, Chemical Engineering Science, 66 (16), 3701-3709. https://doi.org/10.1016/j.ces.2011.05.013
[88] Schwarz, B. C., Devinny, J. S., Tsotsis, T. T., 2001. A biofilter network model—importance of the pore structure and other large-scale heterogeneities, Chemical Engineering Science, 56 (2), 475-483. https://doi.org/10.1016/S0009-2509(00)00251-7
[89] Hinebaugh, J., Bazylak, A., 2010. Condensation in PEM fuel cell gas diffusion layers: a pore network modeling approach, Journal of the Electrochemical Society, 157 (10), B1382. https://doi.org/10.1149/1.3467837
[90] Jamshidi, S., Boozarjomehry, R. B., Pishvaie, M. R., 2009. Application of GA in optimization of pore network models generated by multi-cellular growth algorithms, Advances in Water Resources, 32 (10), 1543-1553. https://doi.org/10.1016/j.advwatres.2009.07.007
[91] Ebrahimi, A. N., Jamshidi, S., Iglauer, S., Boozarjomehry, R. B., 2013. Genetic algorithm-based pore network extraction from micro-computed tomography images, Chemical Engineering Science, 92, 157-166. https://doi.org/10.1016/j.ces.2013.01.045
[92] Vrettos, N. A., Imakoma, H., Okazaki, M., 1989. Characterization of porous media by means of the Voronoi-Delaunay tessellation, Chemical Engineering and Processing: Process Intensification, 25 (1), 35-45. https://doi.org/10.1016/0255-2701(89)85004-4
[93] Wildenschild, D., Vaz, C., Rivers, M., Rikard, D., Christensen, B., 2002. Using X-ray computed tomography in hydrology: systems, resolutions, and limitations, Journal of Hydrology, 267 (3-4), 285-297. https://doi.org/10.1016/S0022-1694(02)00157-9
[94] Ketcham, R. A., Carlson, W. D., 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences, Computers & Geosciences, 27 (4), 381-400. https://doi.org/10.1016/S0098-3004(00)00116-3
[95] Al-Raoush, R., Willson, C., 2005. Extraction of physically realistic pore network properties from three-dimensional synchrotron X-ray microtomography images of unconsolidated porous media systems, Journal of Hydrology, 300 (1-4), 44-64. https://doi.org/10.1016/j.jhydrol.2004.05.005
[96] Bakke, S., Øren, P.-E., 1997. 3-D pore-scale modelling of sandstones and flow simulations in the pore networks, SPE Journal, 2 (02), 136-149. https://doi.org/10.2118/35479-PA
[97] Arns, J.-Y., Sheppard, A., Arns, C., Knackstedt, M., Yelkhovsky, A., Pinczewski, W., 2007. Pore-level validation of representative pore networks obtained from micro-CT images, in Proceedings of the International Symposium of the Society of Core Analysts, 1-12.
[98] Jones, A. C., Arns, C. H., Hutmacher, D. W., Milthorpe, B. K., Sheppard, A. P., Knackstedt, M. A., 2009. The correlation of pore morphology, interconnectivity and physical properties of 3D ceramic scaffolds with bone ingrowth, Biomaterials, 30 (7), 1440-1451. https://doi.org/10.1016/j.biomaterials.2008.10.056
[99] Sheppard, A., Sok, R., Averdunk, H., 2005. Improved pore network extraction methods, in International Symposium of the Society of Core Analysts, Society of Core Analysts, 2125, 1-11.
[100] Rabbani, A., Ayatollahi, S., Kharrat, R., Dashti, N., 2016. Estimation of 3-D pore network coordination number of rocks from watershed segmentation of a single 2-D image, Advances in Water Resources, 94, 264-277. https://doi.org/10.1016/j.advwatres.2016.05.020
[101] Dong, H., Fjeldstad, S., Alberts, L., Roth, S., Bakke, S., Øren, P.-E., 2008. Pore network modelling on carbonate: a comparative study of different micro-CT network extraction methods, in International Symposium of the Society of Core Analysts, Society of Core Analysts, 1-12.
[102] Das, A., Basu, S., Kumar, A., 2019. Modelling of shale rock pore structure based on gas adsorption, in E3S Web of Conferences, 92: EDP Sciences, 15006. https://doi.org/10.1051/e3sconf/20199215006
[103] Okabe, H., Blunt, M. J., 2004. Prediction of permeability for porous media reconstructed using multiple-point statistics, Physical Review E, 70 (6), 066135. https://doi.org/10.1103/PhysRevE.70.066135
[104] Valvatne, P. H., Piri, M., Lopez, X., Blunt, M. J., 2005. Predictive pore-scale modeling of single and multiphase flow, in Upscaling Multiphase Flow in Porous Media: Springer, 23-41. https://doi.org/10.1007/1-4020-3604-3_3
[105] Gharbi, O., Blunt, M. J., 2012. The impact of wettability and connectivity on relative permeability in carbonates: A pore network modeling analysis, Water Resources Research, 48 (12). https://doi.org/10.1029/2012WR011877
[106] Mostaghimi, P., Bijeljic, B., Blunt, M. J., 2012. Simulation of flow and dispersion on pore-space images, SPE Journal, 17 (04), 1131-1141. https://doi.org/10.2118/135261-PA
[107] Raeini, A. Q., Bijeljic, B., Blunt, M. J., 2018. Generalized network modeling of capillary-dominated two-phase flow, Physical Review E, 97 (2), 023308. https://doi.org/10.1103/PhysRevE.97.023308
[108] Lubis, L., Harith, Z., 2014. Pore type classification on carbonate reservoir in offshore Sarawak using rock physics model and rock digital images, in IOP Conference Series: Earth and Environmental Science, 19 (1): IOP Publishing, 012003. https://doi.org/10.1088/1755-1315/19/1/012003
[109] Xu, S., Payne, M. A., 2009. Modeling elastic properties in carbonate rocks, The Leading Edge, 28 (1), 66-74. https://doi.org/10.1190/1.3064148

[110] Dou, Q., Sun, Y., Sullivan, C., 2011. Rock-physics-based carbonate pore type characterization and reservoir permeability heterogeneity evaluation, Upper San Andres reservoir, Permian Basin, West Texas, Journal of Applied Geophysics, 74 (1), 8-18. https://doi.org/10.1016/j.jappgeo.2011.02.010
[111] Lagree, B., 2014. Modelling of two-phase flow in porous media with volume-of-fluid method, Paris 6.
[112] Cudjoe, S. E., Ghahfarokhi, R. B., 2020. Application of Imaging Techniques in the Characterization of Organic-Rich Shales, Unconventional Hydrocarbon Resources: Techniques for Reservoir Engineering Analysis, 189.
[113] Oyinloye, M., 2021. Analysis and Visualization of 3D pore networks in Pleistocene reef cores from Shurayrah Island (Al Wajh, N Red Sea).
[114] Charlaftis, D., 2021. Assessing sandstone reservoir quality: identifying the reality, Durham University.
[115] Zou, C.N., Zhao, W.Z., Jia, C.Z., Zhu, R.K., Zhang, G.Y., Zhao, X., Yuan, X.J., 2008. Formation and distribution of volcanic hydrocarbon reservoirs in sedimentary basins of China, Petroleum Exploration and Development, 35 (3), 257-271. https://doi.org/10.1016/S1876-3804(08)60071-3
[116] Bolandtaba, S., Skauge, A., 2011. Network modeling of EOR processes: a combined invasion percolation and dynamic model for mobilization of trapped oil, Transport in porous media, 89 (3), 357-382. https://doi.org/10.1007/s11242-011-9775-0
[117] Hammond, P. S., Unsal, E., 2012. A dynamic pore network model for oil displacement by wettability-altering surfactant solution, Transport in porous media, 92 (3), 789-817. https://doi.org/10.1007/s11242-011-9933-4
[118] Qin, C.-Z., Hassanizadeh, S. M., 2015. Pore-network modeling of solute transport and biofilm growth in porous media, Transport in Porous Media, 110 (3), 345-367. https://doi.org/10.1007/s11242-015-0546-1
[119] Lu, C., Yortsos, Y. C., 2001. A pore-network model of in-situ combustion in porous media, in SPE International Thermal Operations and Heavy Oil Symposium, Porlamar, Margarita Island, Venezuela. https://doi.org/10.2118/69705-MS
[120] Vickers, N. J., 2017. Animal communication: when i'm calling you, will you answer too?, Current biology, 27 (14), R713-R715. https://doi.org/10.1016/j.cub.2017.05.064
[121] Sorbie, K. S., Collins, I., 2010. A proposed pore-scale mechanism for how low salinity waterflooding works, in SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA. https://doi.org/10.2118/129833-MS
[122] Watson, M. G., Bondino, I., Hamon, G., McDougall, S. R., 2017. A pore-scale investigation of low-salinity waterflooding in porous media: Uniformly wetted systems, Transport in Porous Media, 118 (2), 201-223. https://doi.org/10.1007/s11242-017-0854-8
[123] Boujelben, A., McDougall, S., Watson, M., Bondino, I., Agenet, N., 2018. Pore network modelling of low salinity water injection under unsteady-state flow conditions, Journal of Petroleum Science and Engineering, 165, 462-476. https://doi.org/10.1016/j.petrol.2018.02.040
[124] Valvatne, P. H., Blunt, M. J., 2003. Predictive pore-scale network modeling, in SPE Annual Technical Conference and Exhibition, Denver, Colorado. https://doi.org/10.2118/84550-MS
[125] Lopez, X., Blunt, M. J., 2004. Predicting the impact of non-Newtonian rheology on relative permeability using pore-scale modeling, in SPE Annual Technical Conference and Exhibition, Houston, Texas. https://doi.org/10.2118/89981-MS
[126] Lopez, X., Valvatne, P. H., Blunt, M. J., 2003. Predictive network modeling of single-phase non-Newtonian flow in porous media, Journal of colloid and interface science, 264 (1), 256-265. https://doi.org/10.1016/S0021-9797(03)00310-2
[127] Lopez, X., 2004. Pore-scale modelling of non-Newtonian flow, University of London.
[128] Sochi, T., 2010. Flow of non-Newtonian fluids in porous media, Journal of Polymer Science Part B: Polymer Physics, 48 (23), 2437-2767. https://doi.org/10.1002/polb.22144
[129] Sochi, T., 2010. Pore-scale modeling of non-Newtonian flow in porous media, arXiv preprint arXiv:1011.0760. https://doi.org/10.48550/arXiv.1011.0760
[130] Sochi, T., 2010. Computational techniques for modeling non-Newtonian flow in porous media, International Journal of Modeling, Simulation, and Scientific Computing, 1 (02), 239-256. https://doi.org/10.1142/S179396231000016X
[131] Al-Gharbi, M. S., Blunt, M. J., 2003. A 2D Dynamic pore network model for modeling primary drainage, in Proceedings of the ESF Workshop on Multiphase Flow in Porous Media, Delft.
[132] Behbahani, H., Blunt, M. J., 2005. Analysis of imbibition in mixed-wet rocks using pore-scale modeling, SPE Journal, 10 (04), 466-474. https://doi.org/10.2118/90132-PA
[133] Behbahani, H. S., Di Donato, G., Blunt, M. J., 2006. Simulation of counter-current imbibition in water-wet fractured reservoirs, Journal of Petroleum Science and Engineering, 50 (1), 21-39. https://doi.org/10.1016/j.petrol.2005.08.001
[134] Li, J., McDougall, S., Sorbie, K., 2017. Dynamic pore-scale network model (PNM) of water imbibition in porous media, Advances in Water Resources, 107, 191-211. https://doi.org/10.1016/j.advwatres.2017.06.017
[135] Chaouche, M., Rakotomalala, N., Salin, D., Xu, B., Yortsos, Y., 1994. Capillary effects in drainage in heterogeneous porous media: continuum modelling, experiments and pore network simulations, Chemical Engineering Science, 49 (15), 2447-2466. https://doi.org/10.1016/0009-2509(94)E0040-W
[136] Okabe, H., Blunt, M. J., 2007. Pore space reconstruction of vuggy carbonates using microtomography and multiple-point statistics, Water Resources Research, 43 (12). https://doi.org/10.1029/2006WR005680
[137] De Boever, E., et al., 2012. Quantification and prediction of the 3D pore network evolution in carbonate reservoir rocks, Oil & Gas Science and Technology–Revue d'IFP Energies nouvelles, 67 (1), 161-178. https://doi.org/10.2516/ogst/2011170
[138] Piri, M., Blunt, M. J., 2002. Pore-scale modeling of three-phase flow in mixed-wet systems, in SPE Annual Technical Conference and Exhibition, San Antonio, Texas. https://doi.org/10.2118/77726-MS
[139] Alizadeh, A., Piri, M., 2014. Three-phase flow in porous media: A review of experimental studies on relative permeability, Reviews of Geophysics, 52 (3), 468-521. https://doi.org/10.1002/2013RG000433

[140] Piri, M., Blunt, M. J., 2005. Three-dimensional mixed-wet random pore-scale network modeling of two-and three-phase flow in porous media. I. Model description, Physical Review E, 71 (2), 026301. https://doi.org/10.1103/PhysRevE.71.026301
[141] Piri, M., Blunt, M. J., 2005. Three-dimensional mixed-wet random pore-scale network modeling of two-and three-phase flow in porous media. II. Results, Physical Review E, 71 (2), 026302. https://doi.org/10.1103/PhysRevE.71.026302
[142] Hui, M.-H., Blunt, M. J., 2000. Pore-scale modeling of three-phase flow and the effects of wettability, in SPE/DOE SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma. https://doi.org/10.2118/59309-MS
[143] Hui, M.-H., Blunt, M. J., 2000. Effects of wettability on three-phase flow in porous media, The Journal of Physical Chemistry B, 104 (16), 3833-3845. https://doi.org/10.1021/jp9933222
[144] Suicmez, V. S., Piri, M., Blunt, M. J., 2008. Effects of wettability and pore-level displacement on hydrocarbon trapping, Advances in Water Resources, 31 (3), 503-512. https://doi.org/10.1016/j.advwatres.2007.11.003
[145] Suicmez, V. S., Piri, M., Blunt, M. J., 2007. Pore-scale simulation of water alternate gas injection, Transport in Porous Media, 66 (3), 259-286. https://doi.org/10.1007/s11242-006-0017-9
[146] Suicmez, V. S., Piri, M., Blunt, M. J., 2006. Pore-scale modeling of three-phase WAG injection: Prediction of relative permeabilities and trapping for different displacement cycles, in SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, USA. https://doi.org/10.2118/95594-MS
[147] Rhodes, M., Bijeljic, B., Blunt, M. J., 2009. A rigorous pore-to-field-scale simulation method for single-phase flow based on continuous-time random walks, SPE Journal, 14 (01), 88-94. https://doi.org/10.2118/106434-PA
[148] Rhodes, M. E., Bijeljic, B., Blunt, M. J., 2008. Pore-to-field simulation of single-phase transport using continuous time random walks, Advances in Water Resources, 31 (12), 1527-1539. https://doi.org/10.1016/j.advwatres.2008.04.006
[149] Bijeljic, B., Mostaghimi, P., Blunt, M. J., 2011. Signature of non-Fickian solute transport in complex heterogeneous porous media, Physical Review Letters, 107 (20), 204502. https://doi.org/10.1103/PhysRevLett.107.204502
[150] Bijeljic, B., Raeini, A., Mostaghimi, P., Blunt, M. J., 2013. Predictions of non-Fickian solute transport in different classes of porous media using direct simulation on pore-scale images, Physical Review E, 87 (1), 013011. https://doi.org/10.1103/PhysRevE.87.013011
[151] Lu, H., 2008. Investigation of recovery mechanisms in fractured reservoirs, Department of Earth Science and Engineering, Imperial College London.
[152] Hughes, R. G., Blunt, M. J., 2001. Network modeling of multiphase flow in fractures, Advances in Water Resources, 24 (3-4), 409-421. https://doi.org/10.1016/S0309-1708(00)00064-6
[153] Talabi, O., Alsayari, S., Fernø, M. A., Riskedal, H., Graue, A., Blunt, M. J., 2008. Pore-scale simulation of NMR response in carbonates, in Proceedings of the International Symposium of the Society of Core Analysis.
[154] Talabi, O., AlSayari, S., Iglauer, S., Blunt, M. J., 2009. Pore-scale simulation of NMR response, Journal of Petroleum Science and Engineering, 67 (3-4), 168-178. https://doi.org/10.1016/j.petrol.2009.05.013
[155] Idowu, N. A., 2009. Pore-scale modeling: Stochastic network generation and modeling of rate effects in waterflooding, PhD thesis. https://doi.org/10.25560/4436
[156] Idowu, N. A., Blunt, M. J., 2010. Pore-scale modelling of rate effects in waterflooding, Transport in Porous Media, 83 (1), 151-169. https://doi.org/10.1007/s11242-009-9468-0
[157] Bekri, S., Laroche, C., Vizika, O., 2005. Pore network models to calculate transport and electrical properties of single or dual-porosity rocks, in SCA, 35.
[158] Békri, S., Nardi, C., Vizika, O., 2004. Effect of wettability on the petrophysical parameters of vuggy carbonates: network modeling investigation, in International Symposium of the Society of Core Analysts, Abu Dhabi, UAE, 5-9 October.
[159] Ioannidis, M., Chatzis, I., 2000. A dual-network model of pore structure for vuggy carbonates, in SCA2000-09, International Symposium of the Society of Core Analysts, Abu Dhabi, UAE.
[160] Bustos, C. I., Toledo, P. G., 2003. Pore-level modeling of gas and condensate flow in two-and three-dimensional pore networks: Pore size distribution effects on the relative permeability of gas and condensate, Transport in Porous Media, 53 (3), 281-315. https://doi.org/10.1023/A:1025026332475
[161] Kharabaf, H., Yortsos, Y. C., 1998. A pore-network model for foam formation and propagation in porous media, SPE Journal, 3 (01), 42-53. https://doi.org/10.2118/36663-PA
[162] Chen, M., Yortsos, Y., Rossen, W., 2005. Insights on foam generation in porous media from pore-network studies, Colloids and Surfaces A: Physicochemical and Engineering Aspects, 256 (2-3), 181-189. https://doi.org/10.1016/j.colsurfa.2005.01.020
[163] Romero-Zeron, L., Kantzas, A., 2005. Evolution of foamed gel confined in pore network models, in Canadian International Petroleum Conference, Petroleum Society of Canada.
[164] Ma, J., Sanchez, J. P., Wu, K., Couples, G. D., Jiang, Z., 2014. A pore network model for simulating non-ideal gas flow in micro-and nano-porous materials, Fuel, 116, 498-508. https://doi.org/10.1016/j.fuel.2013.08.041
[165] Wang, J.-Q., Zhao, J.-F., Yang, M.-J., Li, Y.-H., Liu, W.-G., Song, Y.-C., 2015. Permeability of laboratory-formed porous media containing methane hydrate: observations using X-ray computed tomography and simulations with pore network models, Fuel, 145, 170-179. https://doi.org/10.1016/j.fuel.2014.12.079
[166] Wang, J., Zhao, J., Zhang, Y., Wang, D., Li, Y., Song, Y., 2016. Analysis of the effect of particle size on permeability in hydrate-bearing porous media using pore network models combined with CT, Fuel, 163, 34-40. https://doi.org/10.1016/j.fuel.2015.09.044
[167] Aghabozorgi, S., Rostami, B., 2016. An investigation of polymer adsorption in porous media using pore network modelling, Transport in Porous Media, 115 (1), 169-187. https://doi.org/10.1007/s11242-016-0760-5

[168] Huang, X., Bandilla, K. W., Celia, M. A., 2016. Multi-physics pore-network modeling of two-phase shale matrix flows, Transport in Porous Media, 111 (1), 123-141. https://doi.org/10.1007/s11242-015-0584-8
[169] Wang, X., Sheng, J. J., 2018. Pore network modeling of the Non-Darcy flows in shale and tight formations, Journal of Petroleum Science and Engineering, 163, 511-518. https://doi.org/10.1016/j.petrol.2018.01.021
[170] Tansey, J., Balhoff, M. T., 2016. Pore network modeling of reactive transport and dissolution in porous media, Transport in Porous Media, 113 (2), 303-327. https://doi.org/10.1007/s11242-016-0695-x
[171] Zhan, M.-l., Wei, Y., Huang, Q.-f., Sheng, J.-c., 2015. Study on migration model of fine particles in base soil under the seepage force based on pore network analysis.
[172] Feng, Q., Li, S., Han, X., Wang, S., 2015. Network simulation for formation impairment due to suspended particles in injected water, Journal of Petroleum Science and Engineering, 133, 384-391. https://doi.org/10.1016/j.petrol.2015.06.027
[173] Seetha, N., Raoof, A., Kumar, M. M., Hassanizadeh, S. M., 2017. Upscaling of nanoparticle transport in porous media under unfavorable conditions: Pore scale to Darcy scale, Journal of Contaminant Hydrology, 200, 1-14. https://doi.org/10.1016/j.jconhyd.2017.03.002
[174] Gostick, J., et al., 2016. OpenPNM: A pore network modeling package, Computing in Science & Engineering, 18 (4), 60-74. https://doi.org/10.1109/MCSE.2016.49
[175] Yang, Y., Wang, K., Zhang, L., Sun, H., Zhang, K., Ma, J., 2019. Pore-scale simulation of shale oil flow based on pore network model, Fuel, 251, 683-692. https://doi.org/10.1016/j.fuel.2019.03.083
[176] Esteves, B. F., Lage, P. L., Couto, P., Kovscek, A. R., 2020. Pore-network modeling of single-phase reactive transport and dissolution pattern evaluation, Advances in Water Resources, 145, 103741. https://doi.org/10.1016/j.advwatres.2020.103741
[177] Golparvar, A., Zhou, Y., Wu, K., Ma, J., Yu, Z., 2018. A comprehensive review of pore scale modeling methodologies for multiphase flow in porous media, Advances in Geo-Energy Research, 2 (4), 418-440. https://doi.org/10.26804/ager.2018.04.07
[178] Qin, C., 2015. Water transport in the gas diffusion layer of a polymer electrolyte fuel cell: Dynamic pore-network modeling, Journal of the Electrochemical Society, 162 (9), F1036. https://doi.org/10.1149/2.0861509jes
[179] Fatt, I., 1956. The network model of porous media, Transactions of the AIME, 207 (01), 144-181. https://doi.org/10.2118/574-G
[180] Mahanta, B., Vishal, V., Ranjith, P., Singh, T., 2020. An insight into pore-network models of high-temperature heat-treated sandstones using computed tomography, Journal of Natural Gas Science and Engineering, 77, 103227. https://doi.org/10.1016/j.jngse.2020.103227
[181] Foroozesh, J., Abdalla, A. I. M., Zivar, D., Douraghinejad, J., 2021. Stress-dependent fluid dynamics of shale gas reservoirs: A pore network modeling approach, Journal of Natural Gas Science and Engineering, 95, 104243. https://doi.org/10.1016/j.jngse.2021.104243
[182] Mehmani, A., Verma, R., Prodanović, M., 2020. Pore-scale modeling of carbonates, Marine and Petroleum Geology, 114, 104141. https://doi.org/10.1016/j.marpetgeo.2019.104141
[183] Bultreys, T., De Boever, W., Cnudde, V., 2016. Imaging and image-based fluid transport modeling at the pore scale in geological materials: A practical introduction to the current state-of-the-art, Earth-Science Reviews, 155, 93-128. https://doi.org/10.1016/j.earscirev.2016.02.001
[184] Morales, V. L., Dentz, M., Willmann, M., Holzner, M., 2017. Stochastic dynamics of intermittent pore-scale particle motion in three-dimensional porous media: Experiments and theory, Geophysical Research Letters, 44 (18), 9361-9371. https://doi.org/10.1002/2017GL074326
[185] Sadeghnejad, S., Enzmann, F., Kersten, M., 2021. Digital rock physics, chemistry, and biology: challenges and prospects of pore-scale modelling approach, Applied Geochemistry, 131, 105028. https://doi.org/10.1016/j.apgeochem.2021.105028
[186] Hoteit, H., Firoozabadi, A., 2008. An efficient numerical model for incompressible two-phase flow in fractured media, Advances in Water Resources, 31 (6), 891-905. https://doi.org/10.1016/j.advwatres.2008.02.004
[187] Grima, A. P., Wypych, P. W., 2011. Investigation into calibration of discrete element model parameters for scale-up and validation of particle–structure interactions under impact conditions, Powder Technology, 212 (1), 198-209. https://doi.org/10.1016/j.powtec.2011.05.017
[188] Dominguez, G., 1992. Carbonate reservoir characterization: A geologic-engineering analysis, Part I, Elsevier.
[189] Unsal, E., Dane, J., Dozier, G. V., 2005. A genetic algorithm for predicting pore geometry based on air permeability measurements, Vadose Zone Journal, 4 (2), 389-397. https://doi.org/10.2136/vzj2004.0116
[190] Fischer, U., Celia, M. A., 1999. Prediction of relative and absolute permeabilities for gas and water from soil water retention curves using a pore-scale network model, Water Resources Research, 35 (4), 1089-1100. https://doi.org/10.1029/1998WR900048
[191] Dillard, L. A., Blunt, M. J., 2000. Development of a pore network simulation model to study nonaqueous phase liquid dissolution, Water Resources Research, 36 (2), 439-454. https://doi.org/10.1029/1999WR900301
[192] Gostick, J. T., 2017. Versatile and efficient pore network extraction method using marker-based watershed segmentation, Physical Review E, 96 (2), 023307. https://doi.org/10.1103/PhysRevE.96.023307
[193] Sheppard, A. P., Sok, R. M., Averdunk, H., 2004. Techniques for image enhancement and segmentation of tomographic images of porous materials, Physica A: Statistical Mechanics and its Applications, 339 (1-2), 145-151. https://doi.org/10.1016/j.physa.2004.03.057
[194] Thompson, K. E., Willson, C. S., Zhang, W., 2006. Quantitative computer reconstruction of particulate materials from microtomography images, Powder Technology, 163 (3), 169-182. https://doi.org/10.1016/j.powtec.2005.12.016
[195] Rabbani, A., Jamshidi, S., Salehi, S., 2014. An automated simple algorithm for realistic pore network extraction from micro-tomography images, Journal of Petroleum Science and Engineering, 123, 164-171. https://doi.org/10.1016/j.petrol.2014.08.020

[196] Bultreys, T., Singh, K., Raeini, A.Q., Ruspini, L.C., Øren, P.-E., Berg, S., Rücker, M., Bijeljic, B., Blunt, M.J., 2020. Verifying pore network models of imbibition in rocks using time-resolved synchrotron imaging, Water Resources Research, 56 (6), e2019WR026587. https://doi.org/10.1029/2019WR026587
[197] Bondino, I., Hamon, G., Kallel, W., Kac, D., 2013. Relative permeabilities from simulation in 3D rock models and equivalent pore networks: Critical review and way forward1, Petrophysics, 54 (06), 538-546.
[198] Berryman, J. G., Blair, S. C., 1987. Kozeny–Carman relations and image processing methods for estimating Darcy's constant, Journal of Applied Physics, 62 (6), 2221-2228. https://doi.org/10.1063/1.339497
[199] Singh, K., Menke, H., Andrew, M., Lin, Q., Rau, C., Blunt, M.J., Bijeljic, B., 2017. Dynamics of snap-off and pore-filling events during two-phase fluid flow in permeable media, Scientific Reports, 7 (1), 1-13. https://doi.org/10.1038/s41598-017-05204-4
[200] Schlüter, S., Li, T., Vogel, H., Berg, S., Wildenschild, D., 2017. Time scales of relaxation dynamics during hydraulic non-equilibrium in two-phase flow, Water Resources Research, 53, 4709-4724. https://doi.org/10.1002/2016WR019815
[201] Armstrong, R. T., McClure, J. E., Berrill, M. A., Rücker, M., Schlüter, S., Berg, S., 2016. Beyond Darcy's law: The role of phase topology and ganglion dynamics for two-fluid flow, Physical Review E, 94 (4), 043113. https://doi.org/10.1103/PhysRevE.94.043113
[202] Reynolds, C. A., Menke, H., Andrew, M., Blunt, M. J., Krevor, S., 2017. Dynamic fluid connectivity during steady-state multiphase flow in a sandstone, Proceedings of the National Academy of Sciences, 114 (31), 8187-8192. https://doi.org/10.1073/pnas.1702834114
[203] Liu, Y., Slotine, J.-J., Barabási, A.-L., 2011. Controllability of complex networks, Nature, 473, 167-176. https://doi.org/10.1038/nature10011