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An Investigation into Preserving Spatially-distinct Pore Systems in Multi-Component Rocks using a Fossiliferous Limestone Example

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Abstract
Limestones containing abundant disc-shaped fossil \textit{Nummulites} can form significant hydrocarbon reservoirs but they have a distinctly heterogeneous distribution of pore shapes, sizes and connectivities, which make it particularly difficult to calculate petrophysical properties and consequent flow outcomes. The severity of the problem rests on the wide length-scale range from the millimetre scale of the fossil’s pore space to the micron scale of rock matrix pores. This work develops a technique to incorporate multi-scale void systems into a pore network, which is used to calculate the petrophysical properties for subsequent flow simulations at different stages in the limestone’s petrophysical evolution. While rock pore size, shape and connectivity can be determined, with varying levels of fidelity, using techniques such as X-ray computed tomography (CT) or scanning electron microscopy (SEM), this work represents a more challenging class where the rock of interest is insufficiently sampled or, as here, has been overprinted by extensive chemical diagenesis. The main challenge is integrating multi-scale void structures derived from both SEM and CT images, into a single model or a pore-scale network while still honouring the nature of the connections across these length scales. Pore network flow simulations are used to illustrate the technique but of equal importance, to demonstrate how supportable earlier-stage petrophysical property distributions can be used to assess the viability of several potential geological event sequences. The results of our flow simulations on generated models highlight the requirement for correct determination of the dominant pore scales (one plus of nm, µm, mm, cm), the spatial correlation and the cross-scale connections.

Key words: Carbonates; \textit{Nummulites}; Multi-scale pore network; Two-phase flow

1. Introduction
Over the last decade, a considerable body of work has focused on using pore-scale images of rocks to derive quantitative estimates of emergent physical properties, such as those associated with fluid flow (see Blunt et al. 2013 for a comprehensive review). The vast majority of approaches use three-dimensional (3D) digital rock models, at a small scale, derived either through tomographic methods (e.g. Vinegar et al. 1987, Flannery et al. 1987; Ketcham and Carlson, 2001; Arns et al. 2005), or as reconstructed from 2D images (e.g. Øren and Bakke, 2003; Okabe et al. 2004; Wu et al. 2006; Kopf et al. 2007; Chen and Wang, 2010; Tahmasebi et al. 2012). The tomographic grey-level images are further segmented into two phases, solid components and the pore space, although in some studies, fluid phase distributions are also determined (Pak et al. 2015). These provide 3D solid-pore (binary)

\footnote{Authorship statement:
Dr Zeyun Jiang, PhD, wrote the manuscript, clarified the ideas, developed the methodology, and carried out the analysis on pore network simulations;
Prof Gary D. Couples, PhD, pioneered at the ideas and the framework with many in-depth interpretations of numerical results;
Dr Helen Lewis, PhD, conceived the ideas, steered the development and was regularly instrumental in guidance;
Dr Alessandro Mangione, PhD, provided Nummulites templates and basic geological knowledge plus quantified characteristics of Nummulitic rocks.}
voxel representations, i.e. tomographic images or reconstructed models. Some of the methods for calculating fluid flow through this solid-pore structure (see Bultreys et al. 2016 for a broad review) operate directly on the pore space model (e.g. Chen and Doolen, 1998; Kang et al. 2006; Ma et al. 2010; Raeini et al. 2012), while others simplify the pore space into a pore network model (e.g. Lindquist et al. 2000; Jiang et al. 2007; Dong and Blunt, 2009).

Techniques to characterise, replicate or quantify the pore (void) distribution mainly focus on using an actual rock specimen as a template for deriving a digital rock model. Some combination of X-ray CT, SEM, and optical petrographic data is typically utilised to generate 3D models from which the pore-space models are extracted (e.g. Prodanovic et al. 2014; Hebert et al. 2015; Soulaine et al. 2016; Lin et al. 2016). However, for some rocks, the pore-size range is so large that a single image cannot capture the whole pore distribution. Consequently, there is an insufficient number, abundance and frequency of fractal properties (e.g. pore size, pore tortuosity) present across this large range of length scales, so even the fractal models (e.g. Xu 2015) are not useful in this case. Different sampled volumes, and potentially different sampling techniques can be used to create digital rock models at each scale, but the authors do not know of any published approach to combine those models into a single unified model that is suitable at the highest resolution required by the size of the smallest pores resolved, and from which the pore system could be extracted and used in the normal way.

Such separation of imaging scales, and then the extraction of pore systems at each required scale, has been mainly used in two ways worldwide: pore network integration and pore model generation, corresponding to the two workflows shown in Fig. 1. The multiscale pore network integrated using the approach of Jiang et al. (2013) is capable of honouring the pore structure spanning multiple orders of magnitudes, e.g. from µm to mm, and so can predict petrophysical properties (e.g. porosity, permeability, capillary pressure) accurately. Aiming to reduce the two-scale network size significantly, Bultreys et al. (2015) introduce virtual links that are assigned with pre-computed properties to represent local microporous regions, into a macropore network. To tackle spatial distribution of micropores, meanwhile, a deterministic approach is proposed in Prodanovic et al. (2014) and Mehmani et al. (2015) by populating the microporosity with a pore network shrunk by a given factor, which can be estimated by experiments such as Mercury Injection Capillary Pressure (MICP). Both validation and good results are reported by these authors, however the multiscale network technique is unsuited to materials where the different-sized pore systems occur in distinct spatial regions, and where preservation of that spatial arrangement is considered to be important. This paper addresses that situation, describing a new pore model generation method (as illustrated in Fig. 1 as operation (3) that combines original models (a) and (d) into model (f)) that allows the characteristics of multi-scale pore systems to be retained and to be represented in appropriate spatial arrangements. We illustrate the first version of this method by using it to assess the flow behaviours of a dolomitised, fossiliferous limestone in which the spatially-distinct fossils have partially- or fully-preserved voids that occur in a very precise arrangement, being remnants of the living chambers of the animal, that can be orders of magnitude larger than the sizes of pores in the surrounding rock matrix.

In the limestone sample used for the case study, two distinct pore systems exist. One is the residual void space of the fossil tests of Nummulites (Fig. 2), consisting of chambers and connections that are distributed in a spiral pattern inside the bounding surface, with individual fossils varying from mm to cm in size. The other pore space is the inter-crystalline pores in the surrounding fine-grained rock matrix, with pores ranging from 1-10 microns in diameter. These matrix pores have a spatially random distribution, which is very different from the ordered voids of the Nummulites spirals in terms of length-scale, shape and spatial location. Nummulites can have chambers up to 10s of millimetres in diameter, significantly larger than the average matrix pore radii of 10s microns. With current topographies, it is not possible to acquire images that are able to simultaneously describe both Nummulites void structures and matrix pore system, because this would require the creation of a
model with a size on the order of a cm, which would lead to a volume of \( \sim 10^{15} \) voxels (Ketcham et al. 2001; Arns et al. 2005; Garing et al. 2014; Lin et al. 2016; Hebert et al. 2015).

Therefore, it is necessary here to introduce a method so that different pore-space components and multi-scale pore structures can all be preserved in the resulting model with correct spatial arrangements. This method will produce realistic models for extremely complex pore structures, allowing us to perform single- and two-phase flow simulations effectively. However, is such a complex model necessary both here and in the general case? In this paper, we show that the preservation of spatially-distinct pore systems does make a difference in the calculated flow properties, so the answer is that there is a big value in progressing towards the additional complexity when the multi-scale pore space contains spatially distinct regions.

In this paper, we present a new methodology that models the pore systems that have two or more components, each with very different pore sizes located in different regions, identified through: (1) extracting templates of pore-solid structures from images at differing length scales, potentially using different tools (e.g. SEM, CT), and all acquired from potentially different sub-samples (e.g. plugs, sub-plugs or fragments) of a single rock, with the aim being to capture the real pore morphology in each identified component; (2) performing transformations, if required, on the extracted templates; (3) enhancing our pore network extraction so as to allow a better voxel representation of a composite pore system. A *Nummulitic* limestone rock is selected because it matches the requirements listed above for interception purposes. In this case study we demonstrate here the fossils’ images were needed in their pre-dolomitisation state but the available images, from the diagenetically altered rock, showed too many components of diagenesis to be used unadjusted. So, the shapes and sizes of the pore system seen in the tomographic images were used to control the generation of fossil representations using the observed geometric characteristics, and were subsequently checked against published descriptions of similar *Nummulites* species from the fossil record. The methodology certainly has potential applications for other multi-component and complex rocks whether the pore system components are described from existing samples or their analogues or, as here, by a constructed complex geometric shape that is informed by component images but is not generated directly from them. As implied above, the method is designed to work equally well for representing the earlier stages of now altered rocks or for determining how changes in, for example the distribution, density or size of a component affects its petrophysical properties. The methodology is also designed to test if and where the spatial distribution into separated pore networks, here the *Nummulites* fossils and the rock matrix matter.

In Section 2 the main points of the geological system of the case-study are provided together with the use of the new methodology. Section 3 outlines the structural and network modelling methodology for the *Nummulitic* limestone. Section 4 details the impact of pore features and distributions in terms of different parameters, such as *Nummulites* density, size, cementation, corrosion and rock matrix, on single- and two-phase flow.

### 2. Geological Setting

The dolomitised *Nummulitic* limestone is of Eocene age and now forms a hydrocarbon reservoir approximately 2km deep off the north shore of North Africa. Originally deposited in shallow water just off a series of nearshore islands (Beavington-Penny et al., 2008), it originally consisted of a calcium carbonate mud containing abundant *Nummulites* fossils, which are approximately oblate resembling a disc, with diameters varying from a few mm to a few cm. The deposited *Nummulites* often contained partial mud infill though some remained empty at this stage. During burial the calcium carbonate mud, a micrite, was very prone to crystal form change resulting in a general alteration from a needle-dominant form to a more equant form. Crystal and pore size is believed to be in the order of a few microns to tens of microns. During burial, at approximately 1500m depth and at approximately 30 m.y. before present (Mangione, 2016; Mangione et al. 2017) the micrite was replaced by dolomite by addition of calcium ions to the molecular structure. This burial
dolomitisation generally preserved the mineralogy and shape of the *Nummulites*, though not necessarily any calcium minerals contained within them, but core samples of this rock strongly suggest that dolomitisation of the matrix was complete in this reservoir. Mangione (2016) also identifies and illustrates the sequence of less significant diagenetic events, such as calcite cementation, which add complexity to the geological evolution but do not add any fundamentally different elements to the problem. Mangione et al. (2017), used the physical and petrophysical properties of the *Nummulitic* limestone immediately before dolomitisation created using this method, together with the basin evolution derived by basin modelling, to simulate the dolomitisation process and indicate the shape, extent and drivers of the dolomitisation. In this work the emphasis is on the methodology to (1) generate suitable digital models of pore systems where there is a large range of pore network characteristics and the networks have distinct identities, and particularly test if the spatial identities of the different components need to be preserved, and (2) to incorporate network alteration techniques to accommodate past, or potentially future, alterations in the pore systems of these components. Section 4 addresses the consequences for petrophysical properties of the various matrix and fossil types.

The methodology developed was designed to accommodate the very different pore systems, in both pore size groups, here varying from microns to millimetres, and in distinct spatial regions, here represented by the fossils and the matrix. The pore system created must also be able to accommodate both very structured and unstructured pore arrangements. The methodology also needs to be capable of using images of the pore-rock system derived from 3D representations such as from X-ray tomography or SEM as well as to develop equation-driven representations of regular geometric shapes, together with techniques to modify images to represent inferred prior or future diagenetic states.

3. Methodology

The methodology is composed of the following steps:

1. Choosing rock matrix model (see Fig. 1(a));
2. Obtaining templates (see Fig. 1(d) and below) of spatially-distinct pore systems;
3. Integrating (see Fig. (3)) rock matrix and templates into a pore model;
4. Extracting (see Fig. 1(4)) a pore network from the resultant model;
5. Conducting (see Fig. 1(7)) network simulation of single- and two-phase flow.

In the model generation, the actual structural characteristics of a rock matrix might be observed using 2D images such as BSE images or 3D X-ray tomographic reconstructions, or by representing for example now overprinted material with selected analogue images. To match the morphological aspects of rock matrix, we can stochastically reconstruct a 3D model (Fig. 3(a)), or choose an appropriate image (Fig. 1(a)) from an existing database of CT images. So, the chosen rock matrix model is equivalent to the targeting structures in terms of pore geometry and topology. The details are discussed below. Where relevant we use the dolomitised Nummulitic limestone as the example: study petrophysical results are provided in Section 4.

For a spatially-distinct pore system, i.e. a pore structure that differs significantly from its background in both spatial distribution and in length scales, the detailed digital model called a template, can be extracted (see Fig. 1(d)) from a CT image that contains the component, here a *Nummulites*, or be created (see Fig. 3(b)) mathematically by, for a *Nummulites*, the Archimedean spiral equation.

The next step is to superpose the *Nummulites* onto a rock matrix, replacing the voxels of the chosen matrix model with those of the superposed model, to generate digital rock models (Fig. 1(f)). After extracting the pore network for the resultant model, our workflow culminates in the calculation of petrophysical properties (e.g. Fig. 1(i,j)).

3.1 Rock Matrix
In the chosen *Nummulitic* limestone example the rock matrix is observed in thin section and BSE to be micro-porous and somewhat heterogeneous. The matrix pore size ranges from approximately one to several hundred µm (Mangione et al. 2014). That multi-scale matrix could be represented by a multi-scale pore network (see Fig. 1(h)), but for the present purpose, we just need a voxellated model to represent the whole rock. For simplicity, we chose to use a homogeneous matrix model and we do not attempt to represent exactly the details of the real matrix material.

### 3.2 Nummulites Template

*Nummulites* have a test (or shell) shape that varies from fairly flat to sub-globular, with the peripheral edge ranging from sharp to rounded (Racey 1992). *Nummulites* are composed of plani-spirally coiled chambers separated by septa (walls), and they are bilaterally symmetrical about the equatorial plane (Racey 1992, 2001). The initial, central chamber is spherical and the second chamber is generally kidney shaped. The chambers and separating walls are covered by a shell with one or a few small apertures linking to the surrounding rock matrix. The shell material is not solid (as seen in Fig. 4), but possesses nano-tubules.

*Nummulites* preserved in rocks have generally been altered physically and chemically during geological time, and their current structure can differ from the initial. Therefore, the analysis workflow described here includes options to assess the variations in calculated properties related both to differences between individual *Nummulites*, and to differences in geo-historical events. A precise way to obtain a *Nummulites* model is to extract it directly from an X-ray CT image. Fig. 5(a) shows an image slice containing *Nummulites*, and Fig. 5(b, c, d) shows three extracted *Nummulites*.

*Nummulites* extraction from an image is as follows (see Fig. 6):

1. Determine *Nummulites* boundary;
2. Mark out boundaries of individual *Nummulites*;
3. Identify different components of *Nummulites*.

Unfortunately, the very small-scale details of the fossils’ preserved pore systems are not clearly captured via the X-ray tomography because of their lower resolutions and the low grey-level contrast between chambers and nearby walls. Thus, the focus must be to choose an appropriate segmentation algorithm that is sufficiently good (at least, visually) to distinguish the obvious voids and the (mostly) solid parts of *Nummulites*. Through intensive testing, we identify three filters with ImageJ (https://imagej.net) including the mean, median, minimum/maximum filters, which prove suitable for extracting individual *Nummulites* that contains four components (Fig. 6) through the above steps.

The potentially-open boundary areas (see Fig. 6) could play a major role in providing pore connectivity between the internal void space and the surrounding rock matrix; that is, the matrix pores outside of *Nummulites* can be connected to the interior voids through the open areas, which are places where the initial boundary of the test has been corroded or otherwise diagenetically altered. That is, the open boundary areas could potentially be crucial for fluid/gas flow through, in or out of a *Nummulites*. For a single *Nummulites*, the chambers and the open boundary areas form the void space, and the closed boundary areas and chamber walls constitute the solid parts. The nano-tubules shown in Fig. 4 that initially passed through the chamber walls may or may not be preserved after burial and diagenesis. Here, they are not considered because they are far too small to include in the eventual composite model whose voxel resolution is far too coarse to capture such small features. They are a topic of interest for subsequent developments (e.g. Fig. 1(h)).

Having a limited number of extracted *Nummulites* templates, we need to further transform them to capture more diagenetic effects (for instance of corrosion, cementation or precipitation) noted from...
thin sections but not directly observed in tomographic reconstructions. In addition, without extracted
Nummulites being available a feasible way to make Nummulites models (Fig. 3(b)) is to define the
basic geometry (Fig. 2 and Fig. 7) by the Archimedean spiral equations:

\[
\begin{align*}
  x &= r \cos \theta, \\
  y &= r \sin \theta.
\end{align*}
\]  

The void space can be modelled by a sequence of chambers along an Archimedean spiral curve (see
Fig. 2). The intersection segments on the spiral curve, which could be considered as the central lines
of the walls separating the chambers, can be given with a fixed distance (e.g. \(2\pi\)) by a unit vector
\((-\theta \sin \theta + \cos \theta, \theta \cos \theta + \sin \theta\)). We fill in each chamber by a series of balls of different radii in
decreasing order away from each chamber’s centre, as shown in Fig. 7(a), and the corresponding
model is generated by adding a certain degree of randomness to choosing ball radii and locations. We
notice that the void space displays a changing trend with smaller touching and tighter chambers in the
spiral centre, but bigger and scattered chambers outwards. Fig. 7(b) shows the chamber void space,
and the central spiral curves highlight and correlate the chamber positions.

### 3.3 Nummulitic Limestone Model

With a set of Nummulites templates of varying sizes and diagenetic states, and two rock matrix
models, the templates can be superposed onto the physical space previously occupied by rock matrix
voxels, thus forming a Nummulitic limestone model. The Nummulites used can be as extracted from
the images, or resulting from a series of transformations. Possible transformations consist of
alterations in size, in orientation and in void space and can be accompanied by changes in the overall
volume or density, and by adjusting the rock matrix volume. The corresponding parameters used in
building the composite model are: density, size, orientation (angle), void enlarging/shrinking
coefficient, boundary open/close switch, volumetric and pore enlarging/shrinking coefficient for the
rock matrix, plus intersection switch. These are explained below.

#### Density

Density is defined as the number of Nummulites per volume, and is used to adjust the Nummulites
fraction in a model. An approximation for density can be determined from thin section images by
manually identifying and counting Nummulites (Fig. 6(a)).

#### Size

The size of a Nummulites is defined by its three dimensions, e.g. 154×149×43 voxels shown in Fig.
5(b). An example Nummulites might need to be resized as a whole in order to generate Nummulites
with the required features. For example, for a rock matrix model of 2 \(\mu\)m per voxel, the Nummulites
with a resolution of 8.05 \(\mu\)m needs to be enlarged 8.05/2 = 4.025 (i.e. the size coefficient) times.
These magnified Nummulites are then superposed on the rock matrix to obtain a model with a uniform
resolution of 2 \(\mu\)m. To reduce the deviation, we first enlarge or shrink a Nummulites by rounding
down to an integer (e.g. 4) from the floating size coefficient (e.g. 4.025) and then interpolate a number
of rows, columns or layers equidistantly, in X-, Y- or Z-direction. Alternately, a mathematically-
derived model (Fig. 7) of Nummulites can be generated at any chosen resolution, using the
Archimedean spiral approach.

#### Orientation

Nummulites can present a certain pattern of orientations in rocks such as being dominantly horizontal,
or at some angle to the horizontal. To specify orientation, we sequentially rotate the templates (Fig.
5(b, c, d)) around X-, Y- and Z-axis at angles of $\theta_x$, $\theta_y$, and $\theta_z$ sequentially, and re-cast that model into the target voxel arrangement.

**Void Enlarging/Shrinking Coefficient**

The corrosion of *Nummulites* could be considered as the chamber walls (see Fig. 6) being partly or completely dissolved, becoming voids. In contrast, cementation can infill a fraction of the chamber spaces with minerals precipitated during geological history. Corrosion adds volume to the void space while cementation reduces it. To implement these operations, a distance map (Fig. 8) is introduced to define the exact part to be converted from void to solid, or vice versa. The value for each void voxel is defined as the distance to its closest solid voxel, but with zero values for every solid voxel. Setting a threshold $\xi$, all void voxels of distance $\leq \xi$ are converted into additional wall voxels, and all *Nummulites* wall voxels of distance $> \xi$ are converted into additional void voxels, respectively, for the simulation of cementation and corrosion, respectively.

**Boundary Open/Close**

As discussed previously, the open/closed boundary area is one component of a *Nummulites* (Fig. 6). *Nummulites* originally deposited in carbonate muds would always be connected to the outside through their apertures but these could become closed during later cementation. Additionally, *Nummulites* could connect with the outside matrix after a part of shell is corroded as open boundary areas during diagenesis, or through breakage during transport before sedimentation or during compaction with burial. To mimic these alterations, we can open or close a fraction of the boundary areas of each *Nummulites*, where the locations and areas can be selected from measurements, or chosen randomly.

**Volumetric Enlarging/Shrinking**

In many cases a rock matrix model as a whole needs to be enlarged or shrunk to match the resolution associated with the extracted *Nummulites*. This can be mimicked simply by replicating the rock matrix model in X-, Y- and/or Z-direction and cascading the multiple parts symmetrically; see the replicated pattern of rock matrix in Fig. 1(f) as an example.

**Intersection**

From Fig. 9, we observe that *Nummulites* might sometimes touch or intersect each other, where material has been lost. For each *Nummulites* that is to be added into the model, we randomly locate its centre and then address its overlap with others. Within the region surrounding a *Nummulites*, the matrix pore-solid structure will be replaced completely by the *Nummulites*, so the matrix pores make connection to *Nummulites* interior only through boundary open areas. To avoid overlap, we count the number of voxels that overlap with other *Nummulites*, and once there are no overlaps, we stop this process and select the *Nummulites*. Alternately, we can also choose the template with, for example, the smallest number of overlapping voxels, if that is the target.

### 3.4 Pore Network Simulation

All two-phase flow simulations are conducted using the network simulator developed by Ryazanov et al. (2009), on the pore networks that are extracted from the rock models using the method of Jiang et al. (2007). The pore networks are assumed to be strongly water-wet and initially are water-saturated. The displacement is dominated by capillary pressure. To simulate the drainage relative permeability, a receding contact angle is assumed to be zero everywhere, and no water trapping is considered for simplicity.

#### 4. A case-study

#### 4.1 Data preparation for the Nummulitic limestone
Using the 2D image shown in Fig. 10(a), we apply our reconstruction (the patch-based algorithm by Tahmasebi and Sahimi (2012), followed by the optimization by Chen and Wang (2010)) to reconstruct a rock matrix model (Fig. 10(b)) of 400³ voxels, with a resolution of 2.05 µm, called model A. To create an alternate matrix model, called model B, we selected an image (Fig. 10(d)) of 1000³ voxels, with a resolution of 3.003 µm from a database of CT images. The selection was made to match the pore structure determined from the square region in the 2D image shown in Fig. 10(c), so that the selected image (Fig. 10(d)) has the similar pore geometry and the same pore connectivity (see Fig. 10) as the reconstructed model. Model A is homogeneous but model B is heterogeneous although both are isotropic.

From Fig. 10 and Fig. 11, we compare the two matrix models, and the three Nummulites templates (Fig. 5(b, c, d)), in terms of pore size distribution (PSD) and pore connectivity function (PCF, Jiang et al. 2007). Model A has tiny and consistently-sized pores (4.88 ~ 11.81 µm), with the volumetric fraction of the sub-pore space of radii < 8 µm being more than 90%, whereas model B is composed of larger and inconsistently-sized pores ranging from 6.10 ~ 84.27 µm. The three templates all have similar distributions and the original void chamber sizes fall between the pore sizes of model A and B. Note that the Nummulites chamber sizes can be modified through resizing, corrosion and cementation, using image manipulation methods such as those described in Jiang et al. (2007).

When the void-pore space is taken into account, model A has a specific Euler number $\chi$ of $-2.7 \times 10^5$ mm$^3$, which indicates that the pore connectivity is much better than that of model B ($\chi = 2.3 \times 10^4$ mm$^3$). An explanation of this is that only a small number of pores in model B contribute to the pore connectivity. Regarding a Nummulites, the void connectivity mainly comes from the corrosion or cementation, because the chambers are always disconnected from each other at the resolution of 8.05 µm. Hence, it is not meaningful to compare individual Nummulites as such.

To investigate the impact of the void-pore structures on fluid flow, we designed and generated four groups of models shown in Table 1. In these models, Nummulites can be either the original templates given in Fig. 5 or ones that are altered by transformations. The models are coded in this way: the first two groups (i.e. AN) and the second two groups (i.e. BN) are built up based on model A and B, respectively, and N represents Nummulites. The embedded Nummulites can be either corroded or cemented, indicated by a suffix of e (expanding) or s (shrinking) in model codes.

### 4.2 Structure Impact

To assess the impact of the spatially-organised void-pore structure, we compare basic petrophysical properties such as porosity, permeability and relative permeabilities. During drainage, oil pressure is gradually increased at the inlet, and water pressure maintains a constant value at the outlet. Initially, oil replaces water in the network elements of the largest pores connected to the inlet when the required entry pressure is reached; and then more and more network elements associated with smaller pores along the invasion fronts are occupied by oil until all available network elements are filled with oil. The results are given in Fig. 12 for a series of oil-water drainage simulations. Note that the irreducible water saturation is almost zero, as invasion of the smallest network elements occurs at very high oil pressures, which can often not be achieved in reality. Additionally, in each model only the percolating pore space is taken into consideration.

**Rock matrix**

When no Nummulites are embedded in models, such as for ANe0 and BNe0, the flow properties are completely determined by the matrix pore structure. Model B has much larger pores than Model A (25.79 µm vs 5.06 µm, on average), but lower porosity (11.3% vs 20.8%). But the pore connectivities show the opposite effect on flow mobility – many more flow paths exist in model A than in model B. As a result of the combination of pore sizes and connectivity, similar permeabilities (78.81 mD vs 121.82 mD) are obtained. However, the relative permeability curves demonstrate different trends (see
Fig. 12(b, d, f, h)) – the cross-over points of Krw and Kro curves are at $S_w = 0.55$ and 0.73, respectively, which means that model B favours oil to move rather than water, even though the whole system is assumed to be water-wet.

**Nummulites Density**

As Nummulites density increases, the porosity and permeability changes (Fig. 12(a, c, e, g)), as shown in Table 2, for model ANe, ANs, BNe and BNs. Regarding relative permeability, models with prefix AN are more sensitive to the density than are BN models, and ANs have increasing Kro (decreasing Krw) and cross-over points moving to the right by $> 0.1$ water saturation. In comparison, BNs have no notable change or motion. Through structure analysis, we note that the pore-void structures are dominated by the overlapping and intersection of void chambers, and the increase in density leads to higher connectivity. We also observe that as more Nummulites are added, the influence of rock matrix decreases because major flow paths in the matrix are replaced by void chambers within highly corroded Nummulites or blocked by heavily cemented Nummulites.

**Corrosion and Cementation**

Note that both porosity and permeability decrease in ANs and BNs models, as more-cemented Nummulites are present. The reason is that the multiple cemented Nummulites have deteriorated the pore connectivity in comparison to either model A or model B, even though the cemented Nummulites have much larger void chambers than the matrix pores.

**Spatially-Preserved and Mixed Models**

Here, we create two network models, Ahomo (Fig. 1(g)) and Bhomo (Fig. 1(h)), in which we generated a rock model (Fig. 1(f)) to preserve the spatial arrangement of Nummulites (Fig. 1(d)) and surrounding rock matrix (Fig. 1(a)) using our new methodology (Fig. 1(3)), and have also created a stochastic network (Fig. 1(h)) that combines all the statistical information (see Fig. 1(c)), using a two-scale network model, where the information is obtained from two pore networks (Fig. 1(b, e)). An image of $300^3$ voxels (2.75 $\mu$m per voxel) was resized into a model (Fig. 1(a)) of $102^3$ voxels and so has an altered resolution of $\sim 8.05$ $\mu$m. The Nummulites (Fig. 1(d)) is obtained by transforming the one shown in Fig. 5(c) with open boundary areas and highly corroded void chambers.

We simulate (Fig. 1(7)) for the two network models (Fig. 1(g, h)) both single- and two-phase flow. Key network properties are listed in Table 3, and the simulated capillary pressure and relative permeability curves are also given in Fig. 1(i) and (j). The results indicate that the two workflows shown in Fig. 1 behave differently, although they can provide similar pore networks and permeabilities. This comparison demonstrates the necessity of improving the multi-scale network model (Jiang et al. 2013), aiming to also preserve the spatial characteristics in order to deal with extremely heterogeneous carbonate rocks, including one or more of fossiliferous materials, those with micro-fractures, and those with macro-/ and micro-pores.

Now we can summarise the main observations from these numerical experiments.

1. Corroded Nummulites increase both porosity and permeability if Nummulites chambers are bigger than nearby pores in the rock matrix. Otherwise they continue to act as baffles to fluid flow;
2. Partly cemented Nummulites are more likely to be a negative influence on single-phase flow, i.e. reducing fluid flow pathways (lower permeability);
3. Models containing the spatially preserved pore systems can develop a higher degree of diagenetic change than that which can develop in a matrix-only model, even though both models, and their original rocks, are subject to the same diagenetic event. As a consequence, models with spatially-preserved pore-systems display a much higher uncertainty in estimates...
of macroscopic parameters (e.g. relative permeability, capillary pressure) than do matrix-only models.

5. Conclusions

We have introduced a new methodology to create rock models that contain spatially-distinct pore-system components. We apply this method to the example of a fossiliferous limestone, where the void spaces in the fossils are very different to the pore system in the surrounding rock matrix. The resulting models permit us to examine the single-and multi-phase flow impacts of variations in the pore structure of the fossil components associated with cementation or chemical corrosion and the density of fossils, along with how these characteristics give different answers with different matrix types. It is clear that the extreme size-gap and the various spatial organizations of the pore/void spaces in Nummulitic limestones causes not only pore channels to have high tortuosity but also pore connectivity to occur at multiple levels. Our Nummulitic models highlight the requirement for correct determination of the dominant pore scales (nm, µm, mm or cm), the spatial correlation and the cross-scale connections, aiming to create multiscale networks capable of fully capturing the heterogeneous structures in carbonate rocks with larger volume whenever possible. They provide a method of representing the distinct pore components of a rock as either spatially distinctive or otherwise and permit a comparison of the consequences of this decision. They also allow representation of the pore systems from rock-derived images or from equation-driven numerical representations, together with tools to alter either one to accommodate observed, expected or speculative burial, deformational or diagenetic alterations. The methodology is flexible enough to be used for other multi-component rocks or sediments.

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### Tables

<table>
<thead>
<tr>
<th>Number of Nummulites</th>
<th>1</th>
<th>2</th>
<th>5</th>
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<tr>
<td>ANe</td>
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<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
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<tr>
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<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
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</tbody>
</table>

| Model code characters | A - Model A; B - Model B; N - Nummulites; e - expanded/corroded; s - shrinked/cemented |

Table 1. A set of resultant models by embedding a number of *Nummulites* into matrix models. The model in the 3\(^{rd}\) row and 4\(^{th}\) column is coded as ANs5, for instance, denoting that it is generated by embedding 5 cemented *Nummulites* into the matrix model A. For each resultant model, only one slice is shown in the 2\(^{nd}\), 3\(^{rd}\) and 4\(^{th}\) columns but a 3D view is given in the 4\(^{th}\) column, where the colours represent different components (see Fig. 6).
### Property Models

<table>
<thead>
<tr>
<th>Models</th>
<th>With no Nummulites</th>
<th>With 10 Nummulites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Porosity (%)</td>
<td>Permeability (mD)</td>
</tr>
<tr>
<td>ANe</td>
<td>20.88</td>
<td>78.81</td>
</tr>
<tr>
<td>ANs</td>
<td>20.88</td>
<td>78.81</td>
</tr>
<tr>
<td>BNs</td>
<td>11.3</td>
<td>121.81</td>
</tr>
<tr>
<td>BNs</td>
<td>11.3</td>
<td>121.81</td>
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</table>

Table 2. Petrophysical properties changes as *Nummulites* density increase.

### Models

<table>
<thead>
<tr>
<th>Models</th>
<th>Nodes</th>
<th>Bonds</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock matrix (Fig. 1(a, b)) (102³ voxels, 2.75 µm/voxel)</td>
<td>1339</td>
<td>2480</td>
<td>25.27</td>
<td>1865.72</td>
</tr>
<tr>
<td>Nummulites (Fig. 1(d, e)) (510³ voxels, 8.05 µm/voxel)</td>
<td>1348</td>
<td>2450</td>
<td>10.01</td>
<td>0.253</td>
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<tr>
<td>Ahomo (Fig. 1(g))</td>
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<td>35.38</td>
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<td>Bhomo (Fig. 1(h))</td>
<td>242674</td>
<td>571729</td>
<td>31.87</td>
<td>3627.85</td>
</tr>
</tbody>
</table>

Table 3. Comparison of our two methods – spatially-preserved (Ahomo) and integrated network (Bhomo) models.
Fig. 1. Two workflows moving from pore voxel representations to petrophysical properties: multi-scale pore network and model generation. The former developed by Jiang et al. (2013) mainly consists of extracting (1, 2) pore networks (b, e) from pore voxel representations (a, d), computing (5) statistical information (c), and generating (6) multi-scale pore network (h). The latter, first presented in this paper, involves the generation (3) of a complex pore model (f) based on various information obtained from one or more of a series of images ((a, d), e.g. CT, SEM) and the extraction (4) of a pore network (g) from the pore voxel representations. The workflows aim to capture the spatially preserved network, which is further characterized by two-scale stochastic networks (i, j) for detailed petrophysical property assessment.
model using the method of Jiang et al. (2007). Both workflows culminate in the network simulation (7) of petrophysical properties (e.g. (i) – capillary pressure, (j) – relative permeability).

Fig. 2. Schematic diagram of a Nummulites (http://vmek.oszk.hu)

Fig. 3. Model generation of the pore system in Nummulitic rock. (a) a reconstructed rock matrix model, excluding the black disk region, of a homogeneous background pore structure; (b) a created Nummulites templates (model) using the Archimedean spiral equation in the region corresponding to the black disk; (c) the pore network extracted from the resultant model by embedding the Nummulites template in the black disk region, where network nodes are represented by balls, and network bonds by cylinders.

Fig. 4. Evidence of nano-scale tubes penetrating (partially or completely) the external shell of a fossil. Scale bar is 200 microns.
Fig. 5. Extracting *Nummulites* from 3D X-ray CT images: (a) one slice of one *Nummulites* 3D image; (b) a *Nummulites* extracted from that image, (c) and (d) *Nummulites* extracted from other X-ray CT images.

Fig. 6. View of the *Nummulites* shown in Fig. 5(b): (a) Cross showing a single slice from the reconstructed tomographic image with *Nummulites* in middle left as shown by dashed lines; (b) orthoslice view of *Nummulites* seen in (a) showing four identified components. Four components identified: (I) – open boundary areas, (II) – closed boundary areas, (III) – void chambers, (IV) walls separating chambers.

Fig. 7. Mathematical *Nummulites* model: (a) A *Nummulites* chamber structure and (b) the model specified by Eq. (1) viewed from two different perspectives.

Fig. 8. Simulating the cementation in a *Nummulites*: (a) a (squared) distance map coded by the rainbow scheme – the smallest distance 0s in blue, the biggest distance in red; (b) the initial void space; (c) partly
cemented void space and (d) heavily cemented space. The distance colour bar is on the right.

![Fig. 9. Types of Nummulitic limestones viewed in thin section with the petrographic microscope: Uncemented chambers (a, d), partly cemented (b, e), and heavily dissolved or corroded (c, f). Green colour in (a) and (c) denotes pore space.](image)

![Fig. 10. Creation of a rock matrix model for the micrite and the dolomite matrixes: (a) chosen micrite equivalent 2D training image, (b) its reconstructed matrix model A, (c) a BSE image from a thin section of the dolomitised reservoir rock showing targeted area in red box, and (d) the matched image for (c) (model B).](image)
Fig. 11. The PSDs (a) and PCFs (b) of matrix model A and B shown in Fig. 10(b, d). Note that (a) also plots the PSDs of the three Nummulites shown in Fig. 5.

Fig. 12. Illustration of the impact on absolute and relative permeability during drainage for the models in Table 1 associated with model A (see Fig. 10(b)) (a, b, c, d) and model B (see Fig. 10(d)) (e, f, g, h), of the corrosion (a, b, e, f) and the cementation (c, d, g, h) of n Nummulites. In (b, d, f, h), Krw/o+n represents the water/oil relative permeability for a model with n embedded Nummulites.
Highlights

. New methodology to model spatially-distinct, multi-scale pore systems;
. Validation of the workflow to represent such multi-component pore systems in fossiliferous carbonate rocks;
. Demonstration using pre-existing flow simulation tools of the complex impact of fossil cementation and dissolution