PORE SCALE MODELLING OF CARBONATE RESERVOIR ROCKS

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ABSTRACT

Generation of realistic 3D Pore Scale Geomodels of carbonate reservoir rocks by simulating the results of the geological processes involved is very complicated. Mainly because the rock may have undergone several phases of diagenetic processes that might have modified or even completely overprinted texture and fabrics of the original carbonate rock. In spite of this problem, a process-based reconstruction technique, originally developed for sandstones, has successfully been extended to the 3D modelling of carbonate reservoir rocks. The input data to the modelling is derived from thin sections. In the present work, we have produced virtual 3D pore scale models of dolostones by simulating the results of the geological processes: particle deposition and diagenetic alteration. These process-oriented models are calibrated to high resolution X-ray Micro Computed Tomography images. Effective properties, such as absolute permeability, electrical resistivity and Nuclear Magnetic Resonance responses, are computed for both the virtual rock models and the Micro Computed Tomography images of the actual rock samples. A comparison of the two data sets shows very good agreement for the effective properties calculated. Numerical pore networks have been successfully extracted and evaluated for the pore scale carbonate rock models.

INTRODUCTION

This study presents the extension of existing sandstone modelling techniques towards the generation of calibrated pore scale models of carbonate reservoir rocks and the calculation of petrophysical properties and flow parameters for these rocks. The approach taken to the modelling of sedimentary rocks is to mimic the results of the main fundamental rock forming geological processes in nature: sedimentation and diagenesis. This approach is more demanding when dealing with carbonate rocks, due to the generally more comprehensive diagenetic alterations. The main challenge is the higher complexity of processes involved in the genesis of carbonates; particularly the fact that primary sedimentary textures and structures may be completely overprinted by diagenetic alterations, causing a wide range of pore and particle sizes.

Several realizations of a carbonate dolostone Pore Scale Geomodel (PSG) have been reconstructed with new algorithms, which take into account depositional textures and the results of diagenetic processes observed in numerous thin sections of carbonate reservoir rocks. The appropriateness of these models is tested by comparing the results with data sets such as X-ray Micro Computed Tomography images (MCT) at different resolutions,

which contain the rock information targeted by the models. The observed pore sizes in many carbonate structures span several orders of magnitude, and were found previously not to be fully resolved in MCT images at 1µm resolution (Arns et al., 2004). This range of scales also puts the applicability of a Representative Elementary Volume (REV) concept for carbonate rocks into question. In that light, the development of a general geometric multiscale model for carbonate rock facies has been reported in Biswal et al. (2007).

The carbonate rock modelled in this study is a dolomitized, bioclastic peloidal grainstone belonging to Dunham's class "recognizable depositional texture" (Dunham, 1962). A first modelling step is to generate the depositional texture based on input data from thin sections and MCT data, and the subsequent modelling of observed diagenetic features in the rock. The resulting models are qualitatively and quantitatively compared with the TS and MCT data by visual inspection, two-point correlation functions and calculated petrophysical properties.

Once a rock-representative model is generated, the extraction of the numerical pore network from the PSG model is straightforward, leading to a unique pore network representation. Numerical network extraction directly from the MCT images, however, is still challenging and under continued development.

MATERIAL AND METHODS

X-ray Micro Computed Tomography And Data Processing

X-ray micro-tomography allows the 3D imaging of rock samples down to sub-micron resolutions. It is a non-destructive technique. The MCT measurements were performed in the European Synchrotron Radiation Facility (ESRF, Grenoble, France) using the ID19 beamline and a FReLoN 2048x2048 pixel camera as detector. During the data acquisition, about 1500 radiographs are recorded, while the sample is rotating from 0 to 180°. A series of 2D slices is then reconstructed (standard filtered back-projection), which are stacked together to build a 3D image (Boller, 2006).

Three pixel resolutions were used with8.06µm (corresponding to a view field of 16 x 8.79 mm^2), 1.4µm (view field: 2.8 x 1.694 mm^2), and 0.7µm (view field: 1.4 x 1.4mm^2) to attain sufficient resolution of the pore size range. As a function of the samples, energies of 40keV, 26KeV, and 19KeV were applied for the 8.06µm, 1.4µm, and 0.7µm resolutions, respectively.

The MCT data are delivered as five stacks of 256 individual images. The MCT data were pre-processed i.e., we performed sub-sampling, filtering and thresholding. Initially, all stacks were cropped into 1000x1000 pixel images and were stacked together to obtain cubes of 1000^3 voxels. In order to remove artefacts and enhance the data quality the cubes were filtered using a Hybrid 3D Median filter. Due to processing reasons, the filtered cubes were sub-sampled into 500^3 voxel cubes and subsequently thresholded to discriminate between the solid phase and the pore space. These pre-processed cubes (8.06µm, 1.4µm and 0.7µm resolution) were used for the direct computation of petrophysical properties, such as porosity, absolute permeabilities and formation factors.

Outline Of The Modelling Procedure

The pore scale carbonate rock reconstruction methodology reproduces the results of the geological processes as observed in the thin sections. The methodology can be used to reconstruct a range of carbonate rocks, but at present, it is limited to carbonates with simple recognisable depositional textures (Dunham, 1962), e.g. with spherical (ooid) or ellipsoidal (peloidal) particles.

The purpose of the reconstruction is to carry out calculations of petrophysical parameters as well as single phase and multiphase flow properties. The presented reconstruction algorithms are largely grid-based, because all calculations of these properties are at present carried out on grid-based rock models. The modelling procedure of the grid-based approach consists of seven steps addressed below:

1. Sedimentation Modelling Of The Depositional Texture

The reconstruction of the depositional texture is an important step in the modelling procedure. The depositional texture often defines the necessary framework for the subsequent diagenetic alterations and the resulting pore space network. The modelling of the depositional texture starts with measurements of the grain size distribution and the shapes of the particles present via image analysis. The sedimentation is modelled by simulating a steepest slope sedimentation process with spherical grains picked randomly from the grain size distribution (Bakke and Øren, 1997).

2. Reshaping And Rearrangement Of The Depositional Texture

Commonly, the depositional particles are non-spherical (except for unaltered ooids). Thus, a subsequent reshaping of the initial spherical particles to ellipsoids is performed through spreading of the spherical grains in order to create space for the ellipsoidal shapes and subsequent reshaping. One, two or three of the ellipsoidal axes may be varied randomly based on measured length distributions. The longest ellipsoidal axes may be oriented totally random, totally parallel or anywhere between the two.

3. Filtering Of The Depositional Texture (Up To 100 Different Depositional Phases)

The filtering function modifies the depositional texture for the diagenesis modelling. The depositional grains or the complementary pore space of the depositional texture may be modified and altered by the diagenetic processes. The depositional grains can be partly or completely dissolved creating moldic porosity; they can be recrystallized to numerous degrees creating sparitic or micritic cements blocking the initial depositional pore space, or be dolomitized enlarging or occluding pore space, eventually also de-dolomitized at a later stage. Identification and quantification of the diagenetic processes observed in the thin section determine the input for the filtering function, which labels the pore space and the identified depositional particle phases as a basis for subsequent diagenesis modelling. The filtering process can be performed totally randomly or as a function of the grain sizes.

4. Calculation Of A Comprehensive Distance Transform (DT) Both In Matrix And Pore.

The diagenetic processes, like i.e. replacive dolomitization or dissolution, starts mainly on the border between the depositional grains and the complementary pore space. In

some carbonate rocks these diagenetic process has not been completed. In other rocks these processes may result in crystal sizes varying with the distance from this border (correlated structures). In order to model such cases, the Euclidean DT (Strzodka and Telea, 2004) is calculated both in the depositional grain matrix and in the complementary pore space. The DT is calculated by an erosion/burning algorithm using a 10-14-17 metric or by calculating the maximum inscribed sphere radius in each voxel of the grid, the latter being more accurate but slower. The resulting comprehensive DT has a value of zero on the depositional particle/pore boundary and increasing values towards the centres of the depositional particles and pores.

5. Distribution Of Replacive Dolomite/Calcite Crystals As A Function Of Depositional Phase And DT

The different filtered depositional grain and pore phases in combination with the comprehensive DT provide a basis for the modelling of diagenesis. With this process, a range of observed carbonate reservoir rocks can be simulated. The crystal size distribution of replacive dolomite or calcite crystals is measured on the available 2D and 3D input data. The dolomite or calcite crystal centres can be deposited in all grid voxels, which satisfy the actual depositional phase and DT criteria. The dolomite and calcite crystals are generated with a modified Pilotti technique as shown in Figure 1 (Pilotti, 2000; Kløv et al., 2003). In this technique a sphere is enclosed by a larger sphere, which is cut by pre-defined crystal planes that are tangents to the inner sphere. The crystal axes may be oriented totally random, parallel or anywhere in between. The crystal shapes may be picked randomly from the measured crystal size distribution or the sizes of the deposited crystals may be functions of the DT values (correlated textures). Varying degrees of overlap of the crystals ensures continuity in the resulting mineral matrix. The overlap may be a function of the filtered phases and/or the DT. The continuity criterion is not implemented for the resulting pore space because pore space continuity depends on the chosen grid resolution.

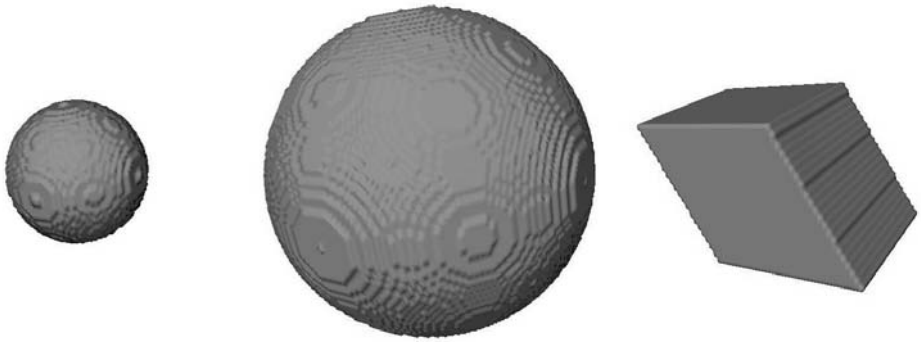

Figure 1: Dolomite crystal modelling. A sphere (left) is surrounded by a larger sphere (middle) which is cut by crystal planes (right) that are tangents to the inner sphere.

6. Distribution Of Micrite As A Function Of Depositional Phase And DT

If the dolomite or calcite crystal sizes are smaller than or near the resolution of the grid, the crystals are treated as micrite, which in this approach is a kind of sub-voxels crystal

mass with a defined microporosity. The micrite may be distributed according to the same criteria as the dolomite/calcite crystals. Micrite may be modelled together with dolomite/calcite crystals as a function of the depositional particle/pore space phase and/or the value of the DT. For modelling implementation convenience, micrite is here defined as a microporous mass (i.e. in the 8µm-resolution model).

7. Optional Distribution Of Cement Like Anhydrite

Our geological modelling allows distribution of cements like gypsum and anhydrite, which was not applied to these models because the MCT images used to extract the input parameters did not show any cements.

The result of the aforementioned procedure is a grid-based model, which is the basis for grid-based calculation of properties like absolute permeability, formation factor and Nuclear Magnetic Resonance (NMR) response as described previously in Øren et al. (2002).

Following the initial, visual comparison between model input (thin section, MCT images, etc.) and resulting PSG, (Fig. 3) the model is quantitatively compared through calculation of two-point-correlation functions on the MCT and the PSG (Fig. 4). A detailed description of the applied method can be found in e.g. Lerdahl et al. (2000). If this statistical control is satisfying, the grid models are used for calculation of the petrophysical properties.

Petrophysical Parameters

Absolute permeabilities and formation factors were directly calculated on the reconstructed model and pre-processed MCT grids. Permeabilities are computed by solving the Navier-Stokes equation, while the formation factors are computed by solving a Laplacian equation as previously reported by Øren et al. (2002).

Two-phase Flow Simulations

Simulation of multiphase flow requires extraction of a numerical pore network, which retains the essential features of the rock model's pore space. The architecture and formats of the pore scale geomodels are designed to fit directly into developed network extraction algorithms (Bakke and Øren, 1997; Øren and Bakke, 2002).

NMR Computations

NMR simulations were directly calculated on the grid based PSG models and on the pre-processed 500^3 MCT volumes. The NMR relaxation response is simulated by a random walk method. The resulting decay curves are inverted to *T2*-distributions by a multi-exponential fitting (Øren et al., 2002). The calculations were performed assuming a water-saturated rock.

RESULTS AND DISCUSSION

Characterization Of The Rock Sample

The rock is classified as a bioclastic peloidal grainstone, containing mainly intergrain macroporosity (~20%) and minor intercrystal microporosity (~10%). The grain size distribution ranges from 48µm to 257µm, the ellipsoidal factor (aspect ratio) from 1.2 to

1.6. The relict peloids are completely replaced by dolomite (Fig. 2). Locally the peloid cores are replaced by sub-microscopic dolomite and the rims or thin fringes of isopachous cement are replaced by coarser planar-e dolomite. Patchy poikilotopic anhydrite replacement is observed (< 8%), and some euhedral dolomite crystals occupy the intergranular pores. The thin section exhibits the occurrence of organic carbon inclusions (Fig. 2).

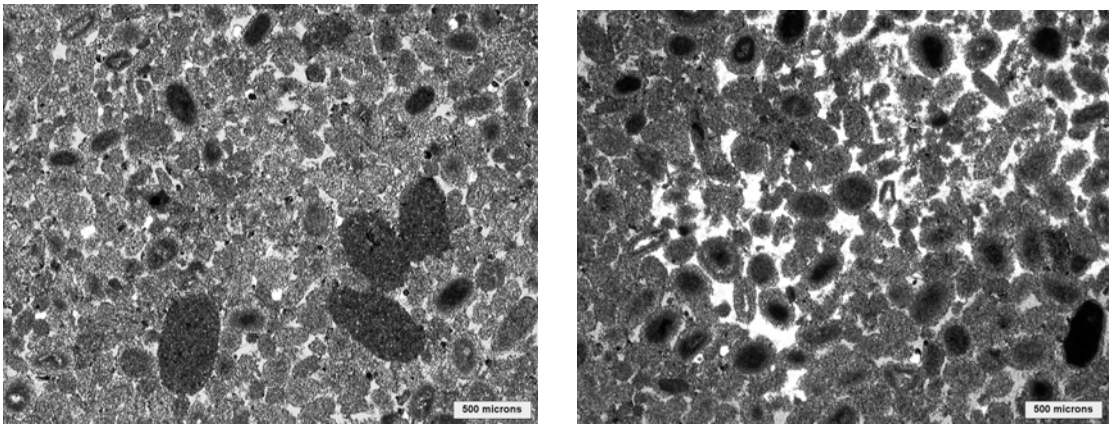

Figure 2: Thin section images of the carbonate sample (light-microscope image under plane-polarized light). Light gray colours represent porosity, white areas (right picture) are poikilotopic anhydrite cement. Scale bars represent 500µm.

Pore scale Geomodelling

The models were generated for three different resolutions: 0.7µm, 1.4 µm and 8 µm, according to the resolution of the MCT images. Grid sizes are 500^3 except for the 8-µm model, which has a 600^3 grid size.

As a rule of the thumb, the model size should be at least ten times bigger than the correlation length at that scale. Table 1 shows the input parameters for all PSG models.

Table 1: Input parameters for the PSG models. G_{min}, G_{max} and G_{mean} depict the minimum, maximum and mean grain size; Ef_{min} and Ef_{max} are the minimum and maximum ellipsoidal factors, respectively. Φ_{IG} is intergrain, Φ_{IX} is intercrystal porosity.

	Grid size (voxels)	*Grid size (µm)*	G_{min} *(µm)*	G_{max} *(µm)*	G_{mean} *(µm)*	Ef_{min}	Ef_{max}	Φ_{IG}	Φ_{IX}	*Dolomite crystal size (µm)*
8 µm	**600^3**	**4800**	**48**	**257**	**102**	**1.2**	**1.6**	**20**	**--**	**--**
1.4 µm	**500^3**	**700**	**48**	**257**	**102**	**1.2**	**1.6**	**20**	**10**	**10 - 20**
0.7 µm	**500^3**	**350**	**48**	**257**	**102**	**1.2**	**1.6**	**20**	**10**	**10 - 20**

From the determined rock parameters, the 8µm model (representing a model size of 4.8mm) may be considered a representative elementary volume (REV), while the 1.4µm (side length of 700µm) and the 0.7µm (side length of 350µm) models are not including features of the rock at larger scales. The same holds true for the MCT data. On the larger plug scale, additional anhydrite cementation is observed whose correlation length cannot be statistically represented at these resolutions. This “competition” between sufficient

model size and model resolution is a main challenge in carbonate modelling. The 8µm model is not capable to resolve the (intercrystal) microporosity present in the sample. Vice versa, the high-resolution models (0.7µm and 1.4µm) grasp the intercrystal porosity, but lack a large proportion of (intergranular) macropore features. Results of the geomodelling are illustrated in Figure 3. 2D sections cut through the models are compared with sections through the MCT images. As Figure 3 shows, the PSG models capture well the features present in the MCT images. All three models represent a multisize model set of the rock, capturing (macro) intergrain- (8µm model) and (micro) intercrystal porosity (1.4µm and 0.7µm models).

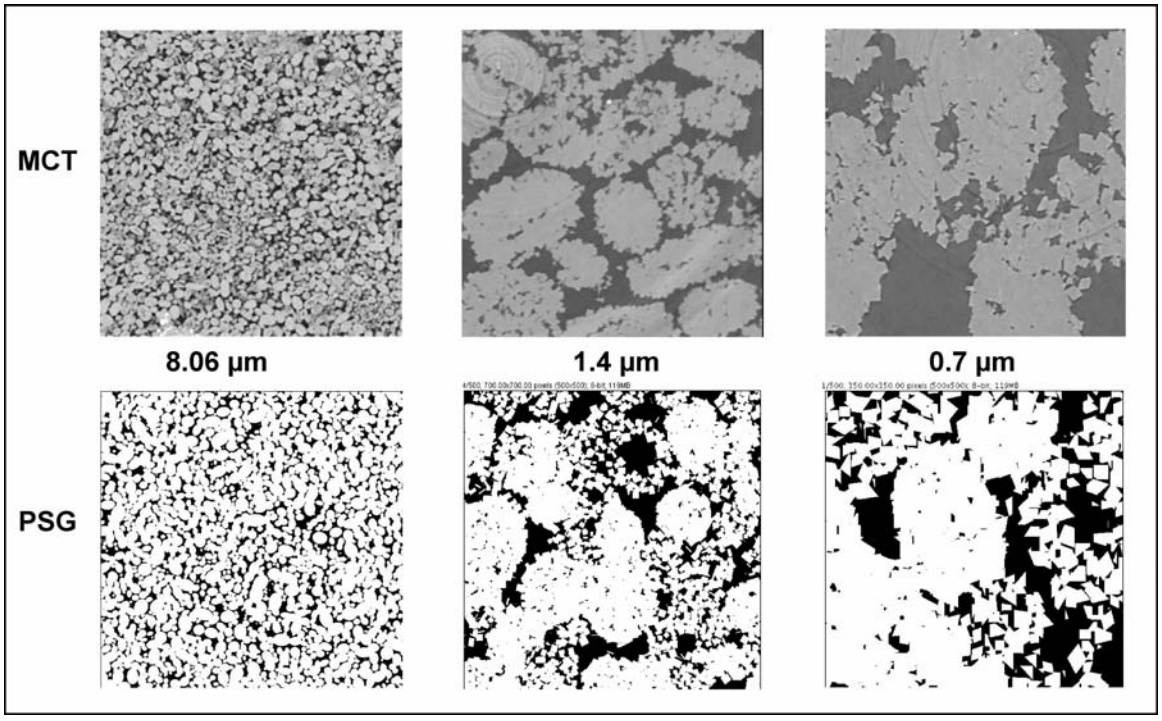

Figure 3: 2D-sections of the MCT images (upper panel) and the PSG models (lower panel) for 8µm (left column), 1.4µm (middle) and 0.7µm (right column).

After initial visual comparison of model outputs and MCT data, two-point-correlation functions were calculated for the 8µm-resolution MCT and PSG, which closely correspond (Fig. 4).

Visual comparison of the models with the MCT images and calculation of the two-point correlation functions as described above, are the two first steps of the calibration, or quality control, of the generated models. As next steps, the available measured petrophysical and reservoir parameters were compared with corresponding parameters calculated on the MCT data and the models.

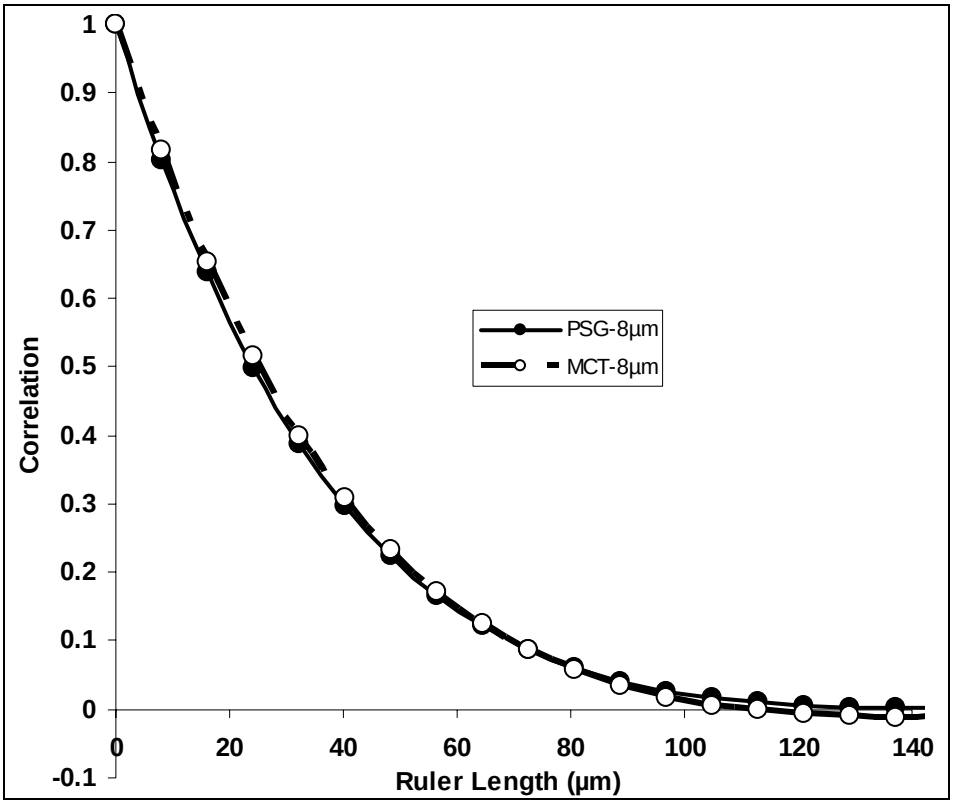

Figure 4: Two-point correlation function from the 8µm MCT data (open circles, dashed line) and the PSG model (filled circles, solid black line).

Grid-based Petrophysical Parameters

Absolute permeabilities and formation factors were calculated in all directions (x-, y-, z-dir) on the MCT and PSG grids for the individual resolutions 8µm, 1.4µm and 0.7µm. The porosity, permeability and formation factor data are summarized in Table 2. Laboratory plug measurements of this sample resulted in 30.1% porosity and 1295mD permeability.

Due to unresolved inter-crystalline porosity, the porosity for the 8µm resolution MCT (20.1%) and PSG (20%) is distinctly lower than the Helium porosity obtained from the plug measurement with 30.1%. The results of the permeability calculations are however in reasonable agreement, with the largest offsets, as expected, being in the high-resolution realizations of both, PSG and MCT volumes.

The calculated 8.06µm and 1.4µm MCT permeabilities overestimate the lab-measured permeability by a factor of 1.6 and 1.9, whereas the 0.7µm MCT calculation results in 1.7-fold lower permeability. The 8µm PSG calculation yields a 2-fold permeability overestimation, while the 1.4µm and 0.7µm PSG permeabilities underestimate the measured permeability by a factor of 3.9. The elevated permeability values of the 8µm PSG and MCT calculations could result from the heterogeneous patchy distribution of anhydrite in the sample. Whilst some areas in the MCT samples show an occurrence of up to 8% poikilotopic anhydrite cement blocking pores and pore throats, vast areas are completely anhydrite free (Fig. 1). The amount of anhydrite in the plug is not determined,

only observed in a 2D CT scan along the length of the plug. The 8.06µm MCT volume contained less than 1% anhydrite.

Table 2: Porosity (Φ) and calculated absolute permeability (k) and formation factors (F) for the MCT data and the PSG models. Plug Measurements resulted in 30.1% porosity and 1295.4 mD permeability.

MCT (500^3)	Φ	k_x (mD)	k_y (mD)	k_z (mD)	k_{Av} (mD)	F_x	F_y	F_z	F_{Av}
8.06 µm	**0.208**	**2108**	**2092**	**2095**	**2098**	**18.5**	**19.1**	**19.3**	**19**
1.4 µm	**0.309**	**2560**	**2117**	**2623**	**2433**	**8.2**	**9**	**8.4**	**8.5**
0.7 µm	**0.312**	**727**	**883**	**741**	**784**	**8.1**	**6.6**	**8.5**	**7.7**
PSG (8µm: 600^3; 1.4µm & 0.7µm: 500^3)									
8 µm	**0.200**	**2360**	**2334**	**2947**	**2547**	**16.2**	**16.3**	**14.3**	**15.6**
1.4 µm	**0.301**	**336**	**310**	**343**	**330**	**11.6**	**11.2**	**10.4**	**11.1**
0.7 µm	**0.301**	**236**	**318**	**390**	**315**	**10.9**	**9.4**	**8.3**	**9.5**

The 8µm PSG was modeled without anhydrite for comparability with the MCT sample. The 8µm-resolution MCT and PSG permeability calculations show an excellent match. However, some deviation occur to the plug measurements due to volume differences and the aforementioned anhydrite cement present in the plug, which is not represented in the MCT and the PSG. The permeability offsets between the high-resolution (1.4µm and 0.7µm) and the 8µm-resolution MCTs and PSGs are expected because the volume of the high-resolution ones are much smaller than the REV. Comparison of the calculated formation factors yield a similar consistency as found for the permeability calculations.

NMR Computations

The NMR T2 relaxation time for a fully saturated reservoir rock is generally governed by the pore size distribution. The NMR T2 responses from the fully water-saturated models were simulated for both the MCT images and the PSG models. The results are compared to the NMR plug measurement at 2 MHz (Fig. 5).

In all NMR simulations, the surface relaxation strength was kept at 1.6×10^{-5} m/sec, the inter echo time was 200µsec, and the diffusion constant was 3.3×10^{-9} m^2/sec.

All T2 distributions calculated from PSG models and MCT images show a bimodal pore-size distribution, whereas the plug measured T2 distribution curve consists of a main peak of the largest pore class around 700ms and an attached shoulder around 130ms (Fig. 5). The graph displays a reasonable fit of the 8µm-resolution PSG (720ms), MCT (640ms) and the experimental data (700ms) for the largest pore size class. The second peaks of the 8µm PSG and MCT T2 distributions (represented as shoulder below 700ms in the measurements) are located at around 120ms (PSG) and 75ms (MCT). These secondary peaks occur rather as single spikes than as solid signals in the 8µm resolutions, because the resolution limit of the models is reached. All 1.4µm and the 0.7µm T2 distribution curves are slightly offset towards smaller pore sizes because the higher-resolution PSG and MCT images do not include a good sampling of the largest pore class. The resolution versus REV sample sizes, however, is strongly rock-type dependent.

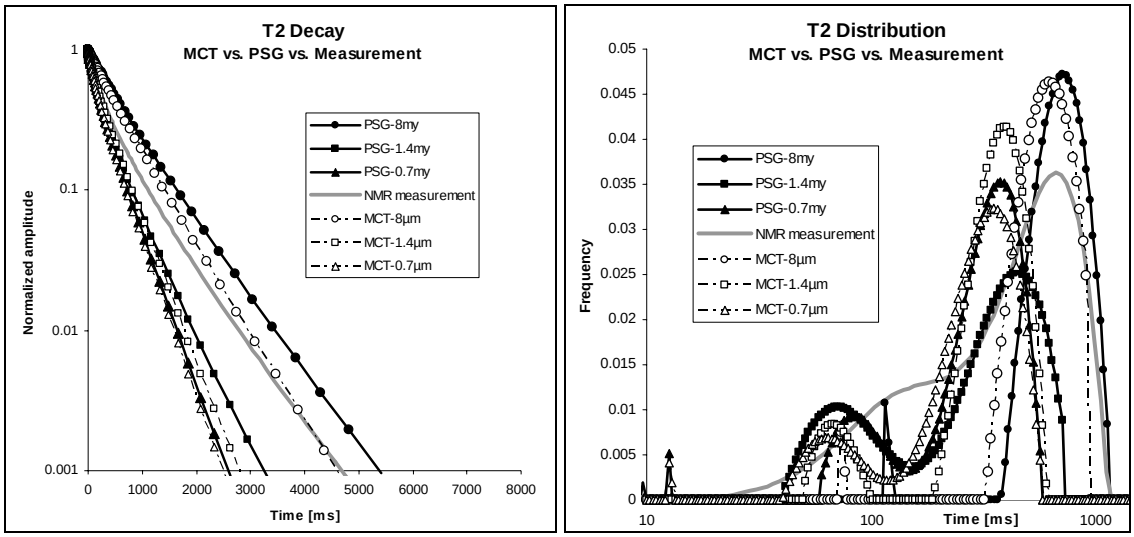

Figure 5: Comparison of measured and calculated T2 decay (left graph) and T2 distributions (right graph). NMR computations on the MCT data are displayed as solid lines for 8µm (filled circles), 1.4µm (filled squares) and 0.7µm (filled triangles). NMR computed from the PSG is shown as dashed (8µm: open circles; 1.4µm: open squares; 0.7µm: open triangles).

Numerical Pore Network Extraction

Extraction of numerical pore networks from the pore scale models is currently a necessary step for carrying out multiphase fluid flow simulations. Numerical pore networks for the different pore scale models were extracted with the network extraction algorithms implemented in ***e-Core*** (further information on the ***e-Core*** technology can be found at http://www.numericalrocks.com/images/stories/final_e-core_product_sheet.pdf).

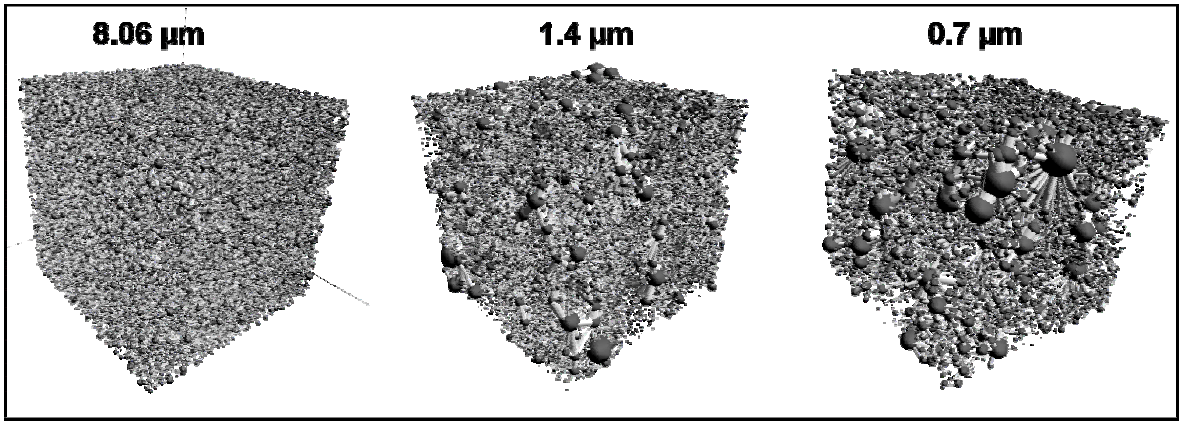

Figure 6. Numerical Pore Networks extracted from PSG models of the grainstone sample for 8µm (left), 1.4µm (middle) and 0.7µm resolution (right).

The extracted pore networks are shown in Figure 6, the network statistics, such as connectivity, node and link radii are given in Table 3.

As mentioned earlier, the 8-µm PSG model was generated without any replacive dolomitization, because with such a resolution, the definition of the crystals will be too poor for the pore-network extraction algorithms.
The target porosity for the observable depositional texture (intergrain porosity) was set to 20%, leaving around 10% intraparticle and intercrystal porosity unrepresented in the model. Because this intraparticle and intercrystal porosity is to be regarded as microporosity, which does not contribute to the main flow connectivity, it may be added randomly to the numerical pore network in a subsequent post-processing step.

Table 3: Network statistics of extracted pore networks for the PSG models (Model resolution: 8µm: 600^3; 1.4µm & 0.7µm: 500^3).

Model Resolution	8 µm	1.4 µm	0.7 µm
No. of nodes	72487	50428	15724
Node radii [µm]; min(avg)max	1.7 (24) 80.9	0.2 (3.7) 62.9	0.14 (2.7) 25.8
No. of links	149336	92965	25718
Link radii [µm]; min(avg)max	0.8 (13.6) 50.13	0.14 (2.4) 25.8	0.07 (1.8) 18.1
Coordination No. (max)	23	228	89
Coordination No. (avg)	4.2	3.6	2.7

The lower maximum connectivity number for the 8-µm PSG model is due to a lack of intercrystal porosity, i.e., replacive dolomitization is not modeled explicitly, yet accounted for as microporosity.
The numerical pore networks extracted from the PSG models enable simulation of multiphase fluid flow, which provide information such as capillary pressure, relative permeability and resistivity indices for primary drainage, water flooding and secondary drainage.
This technology offers the possibility to carry out sensitivity studies, such as the effect on multiphase flow properties caused by variations in pore structure or in distribution of vugs in the dolostones. Such an electronic core laboratory technology has a large potential for calculating “hard-to-get” reservoir properties based on virtual rock models. However, the network-extraction algorithms for carbonate rocks are still under development and testing and results built on the extracted networks of carbonates will be presented at a later stage.

CONCLUSIONS

Calibrated multi-size models of a carbonate reservoir rock have successfully been generated with our PSG technology. The calibrated depositional textures and models are based on input data from plug measurements, thin sections and MCT data.
Petrophysical properties, such as absolute permeability, electrical resistivity and NMR responses were computed for both the virtual rock and the MCT images. The results of these computations are in reasonable agreement with experimental data from the core plug measurements.
Simulations of NMR T2 responses show, in general, an agreement with the largest pore size classes represented in the models, the MCT images and the laboratory

measurements. NMR simulation on the 8µm PSG and MCT closely reproduce the main peak of the NMR plug measurement. Due to the fact that the 1.4µm and 0.7µm PSG and MCT represent very small volumes and a limited pore size range, their peaks are offset to smaller pore sizes.
Numerical pore networks have been successfully extracted from the PSG models by applying available network extraction, thus enabling simulation of multiphase flow through the models.

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