Quantitative pore network analysis and permeability evaluation of porous carbonate reservoir rocks using X-ray computed microtomography images

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Abstract

The texture and the morphology of the pore network exerts and primary control in the fluid storage and migration of geofluids within porous carbonates reservoirs. The architecture of the pore network of porous carbonates are highly variable because of primary depositional variability, diagenesis processes and deformation. This issue represents an important challenge for the characterization and exploitation plan of this type of reservoirs in different industries such as, hydrocarbon, ground water and geothermal energy. This type of rocks is widely studied because they represent important reservoirs for geofluids around the globe. However, there are few studies analyzing the control exerted by the pore network properties (e.g. porosity, pore size distribution, connectivity, tortuosity) on the permeability.

In this study the control exerted by the pore network on the storage and migration capacity in porous carbonates is evaluated by combining synchrotron X-ray computed microtomography (SR micro-CT) and computational fluid dynamics. The studied rock samples are mainly porous grainstones exposed in south and central Italy. Some samples may content deformation structures (i.e. deformation bands) or may be altered by diagenesis. Previous studies have reported permeability differences and significant variabilities of the in-situ hydrocarbon distribution on the studied rocks. The SR micro-CT imaging experiments were performed at the SYRMEP (SYnchrotron Radiation for MEdicinal Physics) beamline (Elettra-Sincrotrone Trieste laboratory, Italy). This beamline was suitable for studying the rocks samples due to its nearly-parallel geometry and a high spatial coherence allowing the phase contrast effects to enhance the visibility of objects with similar linear attenuation coefficients. In this study, the selected spatial resolution of the images is variable (1.0-9.0 μm) depending on the grain size distribution of the rock sample.

The SR micro-CT images were used for both performing a quantitative pore network analysis of the studied rock samples and performing computational fluid dynamics experiments. These experiments consist in simulating a pressure-driven flow by using the lattice-Boltzmann method (LBM) with multiple relaxation time (MRT) model. This method generates viscosity-independent results of permeability. The permeability of the volume was calculated using Darcy’s law once steady conditions were reached. To evaluate isotropy, the results of permeability and the pore network properties were calculated in three dimensions. The results indicate that deformation and diagenetic processes may have and important impact on the pore network properties and therefore on storage (porosity) and migration (permeability) capacity of the studied rocks.

Keywords: Porous carbonates; permeability, X-ray computed microtomography, lattice-Boltzmann method

1 Introduction

During the characterization of geofluid reservoirs, one of the most elusive aspects is obtaining relationships between porosity and permeability. The permeability-porosity cross plots typically show important scattering indicating that permeability also on textural and hydraulic properties of the pore network such as pores size distribution, pores shape, and tortuosity [1,2]. This is of interest in carbonates, where the architecture of the pore network is highly variable because of primary depositional variability, diagenesis processes and deformation. Different attempts have been made to relate the pore-network properties and the permeability in order to describe their control or estimate the value of permeability [3]. However, founding the direct empiric relationships at the pore scale still needing deeper investigations. This kind of investigations can be done using direct fluid simulations of digital rocks characterized by complex porous media [4, 5].

In this study the control exerted by the pore network on the storage and migration capacity in porous carbonates is evaluated by combining synchrotron X-ray computed microtomography (SR micro-CT) and computational fluid dynamics. The studied rock samples are mainly porous grainstones exposed in south (Sicily) and central Italy (Abruzzo). Some samples may content deformation structures (i.e. Deformation Bands, DBs) or may be altered by diagenesis. Previous studies have reported permeability differences and significant variabilities regarding the porosity and permeability [e.g. 6, 7]. Some samples pertain to actual reservoir carbonates rocks where the lithofacies controls the in-situ hydrocarbon distribution [8].

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This work attempts to provide more evidence concerning the control exerted by the effective porosity, specific surface area and tortuosity on permeability in deformed carbonate rocks. This objective has been reached by combining quantitative images analysis and computational fluid dynamics using synchrotron radiation computed microtomography (SR micro-CT) images of deformed carbonate rock samples. We also performed simple quantitative image analysis of the SR micro-CT to explain real situations of actual reservoirs. The SR micro-CT images were acquired at the Elettra - Synchrotron Trieste laboratory (Basovizza, Italy) and processed and analysed as described by Arzilli et al. [9] and Zambrano et al. [10]. The permeability of deformed porous carbonate rocks was computed via LBM, using the PALABOS open source library [11] using an MRT approach in order to ensure that values of permeability are viscosity-independent.

2 Methods

The SR micro-CT imaging experiments were performed at the SYRMEP (Synchrotron Radiation for MEdicinal Physics) beamline (Elettra-Sincrotrone Trieste laboratory, Italy). This beamline was suitable for studying the rocks samples due to its nearly-parallel geometry and a high spatial coherence [12, 13] allowing the phase contrast effects to enhance the visibility of objects with similar linear attenuation coefficients. This beamline is suitable for obtaining 3D images of carbonate rocks and extracting valuable information about pores morphology, connectivity, and permeability at the pore scale [e.g. 9, 14]. In this study, the SR micro-CT experiments and the image processing and analysis were performed following the methodology described by Arzilli et al. [9] and Zambrano et al. [10] using both a monochromatic and a white beam configuration with variable spatial resolution of the images (1.0-9.0 μm).

For the images acquired in the monochromatic beam configuration, the sample-to-detector distance was set to 180 mm (propagation-based phase-contrast mode) and an X-ray energy of 34 keV was selected by a double-crystal Si monochromator. Each sample was placed on a high-resolution rotation stage, and a series of 1800 radiographs (projections) were acquired over a total angular range of 180° with an exposure time/projection of 3.5 sec. Projections were acquired by using a water-cooled, 12-bit, 4008 x 2672 pixels CCD camera (VHR, Photonic Science) with an effective pixel size of 4.5 μm. The camera chip was coupled to a Gadox scintillator screen through a fiber optics taper in order to convert the X-ray into visible light. Applying a 2x2 binning to the detector pixels, an output pixel size of 9.0 μm x 9.0 μm was used for image acquisition. For the experiments in a white beam configuration mode [15], the X-ray energy was set to 22 keV and the X-ray beam was filtered with 1.5 mm Si + 0.025 mm of Mo. The sample-to-detector distance was set at 150 mm and 200 mm. For each sample, 1800 projections were acquired over a total scan angle of 180 ° with exposure time/projection of 2 s, 2.5s or 3.0s (depending on the sample and the quality output image). The detector consisted of a 16 bit, air-cooled, sCMOS camera (Hamamatsu C11440-22C) with a 2048 x2048-pixel chip. The effective pixel size of the detector varies from 1.25 μm to 1.80 μm (depending on the sample), yielding to field of view of approximately 2.5 mm x 2.5 mm.

The 3D image segmentation was performed by the automatic multiphase k-means clustering algorithm, setting 3 to 4 classes of objects, depending on the sample. The segmentation was performed by using the Pore3D software library developed at Elettra [16]. Then, a 3D bilateral filter was applied to the reconstructed data for smoothing the images and preserving edges. The SR micro-CT images were used for both performing a quantitative pore network analysis of the studied rock samples and performing computational fluid dynamics experiments using the open-source software Palabos [11], which is based in lattice-Boltzmann method (LBM). The methodology [5, 17] consists of imposing a single-phase fluid flow through the segmented 3D images by maintaining a fixed pressure gradient between the inlet and outlet faces of the volume, the rest of the faces were padded. The interface pores-voids was converted to bounce-back boundary conditions. It was used a Multiple Relaxation Times approach [18] with a D3Q19 lattice. This method generates viscosity-independent results of permeability. The permeability of the volume was calculated using Darcy’s law once steady conditions were reached. To evaluate isotropy, the results of permeability and the pore network properties were calculated in three dimensions.

From the field velocity volumes (segmented), the effective porosity, specific surface area and tortuosity have been evaluated. The effective porosity (Φ) here is defined as the ratio of the pore volume with a non-zero velocity and the total volume of the sample. The specific surface area (S) is defined as the ratio of the surface in contact with fluid and the total volume. Finally, the method used to evaluate the tortuosity is based on the direct measurement of the shortest distance between two points in the pores [19].

3 Results

The primary results of this work are both the segmented pore space, divided in connected and isolated, and the velocities fields in lattice units (Fig. 1). Whereas, quantitative results correspond to the different measured properties (i.e. permeability, porosity, specific surface area and tortuosity; Fig. 2). The permeability results obtained by simulations are highly consistent (maximum one order of magnitude of difference) to the data reported by previous authors using field [6-8] or laboratory techniques [20, 21]. These considerations allow us to add deeper discussions related to variation of permeability with respect to deformation and diagenetic processes taking place in the studied rocks, as follow.
The results indicate that deformation and diagenetic processes may have an important impact on the pore network properties and therefore on storage (porosity) and migration (permeability) capacity of the studied rocks. The reduction of the effective porosity within the DBs may be related to diagenesis or deformation processes. Grain size reduction, helped by intergranular pressure solution [22], generates an important effective porosity reduction due to both the accommodation of fined-grain residual material in the available pore space and the precipitation of solved solids in adjacent in the pore space [22]. In the first case, pore size may decrease and eventually the micropores may have an insignificant contribution to the flow. The second case, the cementation, is a determinant mechanism for the occlusion and isolation of the porosity as it was observed in the most cemented volumes. In the case of compaction, in a bimodal pore size distribution macropores are more prone to collapse than micropores during inelastic compaction [23]. This observation may in part explain that rocks dominated by macroporosity present the most significative reduction of porosity within the DB with respect to the host rock. However, this is not necessarily true in our case due to the studied rocks may not experience the same deformation conditions.

Additional to the connectivity of the pore network, permeability depends on the effective porosity, specific surface area and tortuosity. Permeability is directly related to the effective porosity, and inversely related to the specific surface area and the tortuosity (Fig. 2). Documented variation in permeability among the evaluated host rock samples is strictly related to the architecture of the pore network expressed by the evaluated properties. However, the method applied in this work is more selective than other traditional methods for assessing the permeability and the textural properties of zones of few millimetres of size.
Figure 2. - Relationship between LBM permeability and a) effective porosity, b) specific surface area, and c) geometrical tortuosity. In blue circles host rock volumes and in red squares deformed volumes.
Results may explain the hydrocarbon distribution in different carbonates facies of actual reservoirs, exposed in Majella Mountain (Central Italy, Abruzzo). For instance, in the same reservoir two facies with similar high-porosity (near 28%) may present totally dissimilar storage and migration capabilities. The 3D X-Ray images indicates that pervious (Bryozoan medium-grained grainstones, gas permeability near to 4.8x10^{-13} m²) facies are highly connected, whereas impervious (Planktonic foraminifera wackestones to mudstones, gas permeability near to 8.4x10^{-17} m²) facies are characterized by isolated porosity (Fig. 3). These results are consistent with both laboratory measurements and field observations [8]. Thus, these results highlight the main control of the connectivity of the pore network for the fluid as has been previously discussed by previous workers [9, 10].

![Figure 3](image.png)

Figure 3. – Comparison of (a) pervious and (b) impervious lithofacies exposed in Majella Mountain. 1) Isolated pores, mainly related to intragrain porosity (bioclastic chambers), 2) Well-connected intergranular pores, normally impregnated of bitumen.

### 4 Conclusions

In this work, the SR micro-CT technique has been using for assessing the pore network of carbonate rocks, computing the permeability and textural properties. We have also used the SR micro-CT to investigate and explain field observations and laboratory results of permeability. The images have been also used for understanding diagenetic processes and their impact on permeability. By analysing the results, we may conclude:

- The permeability is non-linear related to porosity, specific surface area and tortuosity. Further analysis can be implemented to develop reliable equations of these relationships.
- Deformation and diagenesis drive changes that can reduced or enhance locally the permeability.
- Difference in terms of connectivity can explain samples with similar porosity values but with totally different permeability. This represent and important risk for the exploration of geofluids.
References


