

Abstract

The aim of this study is to compare the structural, geometrical and transport parameters of a limestone rock sample determined by X-ray microtomography (XMT) images and laboratory experiments. Total and effective porosity, surface-to-volume ratio, pore size distribution, permeability, tortuosity and effective diffusion coefficient have been estimated. Sensitivity analyses of the segmentation parameters have been performed. The limestone rock sample studied here have been characterized using both approaches before and after a reactive percolation experiment. Strong dissolution process occurred during the percolation, promoting a wormhole formation. This strong heterogeneity formed after the percolation step allows to apply our methodology to two different samples and enhance the use of experimental techniques or XMT images depending on the rock heterogeneity. We established that for most of the parameters calculated here, the values obtained by computing XMT images are in agreement with the classical laboratory measurements. We demonstrated that the computational porosity is more informative than the laboratory one. We observed that pore size distributions obtained by XMT images and laboratory experiments are slightly different but complementary. Regarding the effective diffusion coefficient, we concluded that both approaches are valuable and give similar results. Nevertheless, we wrapped up that computing XMT images to determine transport, geometrical and petrophysical parameters provides similar results than the one measured at the laboratory but with much shorter durations.

1 Introduction

Characterizing the pore rock structure such as the porosity, the total pore–rock interface and the connectivity is essential to evaluate oil or gas production or volume of stored CO₂ in case of geological sequestration for example. Porosity is one of the most important petrophysical parameters as it indicates the total volume of oil, gas or water

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that can be contained in a reservoir. It is essential to differentiate total porosity and open connected or effective porosity which is the real accessible porosity by any fluid. Connectivity as well as permeability and tortuosity indicate the extraction or injection facility. The higher the connectivity and permeability are and the lower the tortuosity is, the higher the extraction or injection flow rate will be. In consolidated rock aquifers, the groundwater flow occurs through discrete openings, i.e. fractures, and only to a small extent in the pore-network of the rock matrix. The migration of solutes and solvents in fractured rock aquifers is therefore determined by the relative contribution of advective flow compared to matrix diffusion transverse to the flow direction, resulting in retardation of the solute. The advection transport is controlled by the permeability of the reservoir (mainly controlled by fracture or preferential flow path as wormhole or karst conduit), whereas the diffusion through the matrix depends of the effective diffusion coefficient, which is linked to tortuosity, effective porosity and cementation factor (Archie, 1942; Fick, 1855). Diffusion in rock, of either gas or liquid phase, could be the rate-limiting or dominant process in many scenarios, such as geologic disposal of radioactive waste (Gillham et al., 1984), contaminant remediation (e.g., Becker and Shapiro, 2003), CO₂ geological storage (Hatiboglu and Babadagli, 2010), and oil and gas recovery (Cui et al., 2004, 2009). Diffusion of hazardous gas or liquid chemicals in construction materials has also become a concern for public health and security (Nestle et al., 2001a, b). Therefore, knowledge of diffusion processes and rates in rocks is important to a better understanding of these problems.

To evaluate all these parameters, different laboratory petrophysical techniques are usually used. Some of them are time consuming and destructive methods, such as mercury pore size measurement or BET (Brunauer–Emmett–Teller) surface analysis. Moreover, these different techniques are realized at different sample scales and may require prior preparation, such as thin section for SEM (Scanning Electron Microscope) analysis for example. Yet, most of the laboratories techniques used and discussed in this article are fully validated.

on soil material using a medical scanner with a large pixel size (0.6 mm). Nevertheless, op. cited authors focused their study to only a few parameters.

Here, we use high resolution X-ray microtomography images to characterize the structural and geometrical parameters of a limestone core rock sample percolated by an acidic solution. We computed and experimentally measured, total and effective porosity, surface-to-volume ratio, permeability, pore size diameter distribution, effective diffusion coefficient, and tortuosity. These parameters are those needed for numerical modeling to evaluate oil and gas deposit volume and extraction flow rate for example. Measuring the pore structure of the same sample before and after a dissolution experiment allows to apply our methodology to two different samples and enhance the use of experimental techniques or XMT images depending on the rock heterogeneity. The focus of the present study is to articulate the potential of variables estimated using XMT images and how these estimates compare with, and complement, traditional laboratory-based measurements.

2 Materials and methods

2.1 Laboratory methodology

2.1.1 Rock sample analysis

The rock sample used in this study is an oolitic limestone almost composed of calcite (CaCO_3), named Bvl. This limestone, usually named Beauval rock, is coming from Beaunotte in Dordogne region in France. It is characterized by a beige color with some shells. The mean connected porosity is usually comprised between 9 and 13%. The core sample diameter and length are respectively 2.5 and 2 cm.

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2.1.2 Laboratory petrophysical characterization

In order to characterize the different geometrical and structural properties of the rock sample before and after the percolation experiments, we used different classical laboratory experiments. These different techniques have been performed following a home-

methodology to avoid too many drying and wetting sample steps. First of all, to evaluate the effective (connected) porosity, we used the triple weighing method. We first measured the dry sample weight after leaving the sample during 48 h in an oven at 40 °C. We then saturated the sample, starting by a sample vacuum step. Afterwards, we left the calcite equilibrated water penetrate into the pore structure and we weighed the saturated and submerged sample weights. This classical method is very time consuming and requires 4 entire days.

Then, we took advantage of the saturated sample state to evaluate the pore size distribution by measuring the retention curve of the sample using a centrifuge and applying various rotation rates as previously done by Luquot et al. (2014b) and Roetting et al. (2015). The technique consists in applying a high gravity field to an initially saturated sample and measuring the drained volume of water. For this purpose, we used a Rotina® 420R centrifuge following the methodology of Reatto et al. (2008) using 6 speed increments up to 4500 rpm. The maximum suction that can be applied to the sample at 4500 rpm is 213 kPa. This technique allows us to measure the effective capillary size distribution and the retention curve $\theta(P)$, where θ is the volumetric water content and P is the capillary pressure (minus suction). By capillarity theory, the minimum radius of a pore that drains at P is given by:

$$r_p = \frac{-2\sigma \cos \alpha}{P} \quad (1)$$

where σ is the surface tension ($72.3 \pm 0.5 \text{ mN m}^{-1}$, Adamson and Gast, 1997) and α is the contact angle ($40 \pm 8^\circ$, Espinoza and Santamarina, 2010). Using Eq. (1), we can convert the measured $\theta(P)$ into an equivalent $\theta(r_p)$ curve. This curve is actually a cumulative pore-size distribution; the water content $\theta(r_p)$ indicates the combined volume

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of all pores with opening radius less than r_p . The measurements were performed twice in the two directions to evaluate the sample anisotropy. Six days were necessary to acquire two times the retention curves in both directions and dry and saturate again the sample for the second measurement.

5 After the centrifuge step, we dried the sample again in an oven during 48 h at 40° and measured again the dry sample weight. We then repeated the triple weighing method to evaluate the initial porosity and took advantage of the saturation state of the sample to perform through-diffusion experiment. Classically, the effective diffusion coefficient as well as the tortuosity factor is measured by liquid phase conservative tracer test (usually iodine) as presented by Boving and Grathwohl (2001) and Luquot et al. (2014a).

Through-diffusion experiments were performed to determine the effective diffusion coefficient and tortuosity/constrictivity ratio before and after the dissolution experiment (Li and Gregory, 1974). The same methodology as the one developed by Luquot et al. (2014b) has been used here. The diffusion cell apparatus consisted of two acryl-glass cells of equal size and volume. The reservoir cell contained a 0.02 mol L^{-1} of potassium iodide tracer solution whereas the sink cell did not contain any tracer at the beginning. We used Beauval rock equilibrated water in both reservoirs and we added several milligrams of sodium azide (NaN_3) to prevent biofilm formation. The mounted rock sample was sandwiched between the sink and reservoir cell. During the experiment, iodide ions diffuse from the reservoir cell into the sink cell through sample BvI. An iodide-specific electrode from Cole–Parmer Instrument CO was used to measure the iodide concentration in the sink cell. More details about the procedure can be found in Luquot et al. (2014b). The aqueous diffusion coefficient for iodide ($D_{\text{aq}} = 1.86 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$) (Robinson and Stokes, 1959) was used to calculate the effective diffusion coefficient D_{eff} . The effective diffusion coefficient was calculated using the equation (van Brakel and Heertjes, 1974; Crank, 1975):

$$D_{\text{eff}} = \frac{\beta l}{C_0} \quad (2)$$

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the sample to calculate the sample permeability. The total injected fluid was 146 cm³, or some 90 pore volumes of sample BvI (initial pore volume = 1.62 cm³).

Outlet water was sampled periodically, acidified to prevent mineral precipitation, and analyzed for concentrations of Ca using inductively coupled plasma-atomic emission spectrophotometry (ICP-AES, IDAEA, Spain). Reaction progress and porosity changes are calculated from the difference between injected and percolated waters, knowing that calcite is the only mineral composing the sample. The volume of dissolved calcite ($\Delta V_{\text{calcite}}(t)$) is calculated as:

$$\Delta V_{\text{calcite}}(t) = \nu Q \int_{t'=0}^{t'=t} \Delta C_{\text{Ca}}(t') dt' \quad (5)$$

where ν is the calcite molar volume ($3.7 \times 10^{-5} \text{ m}^3 \text{ mol}^{-1}$), and ΔC_{Ca} is the difference between the outlet and inlet calcium concentration. Therefore, we can calculate the sample-scale porosity change during the percolation experiment using the following equation:

$$\phi(t) = \phi_0 + \frac{\Delta V_{\text{calcite}}(t)}{V} \quad (6)$$

where V is the total sample volume and ϕ_0 is the initial sample porosity. The error $\epsilon(\Delta C_{\text{Ca}})$ in the change of calcium concentration was estimated using the Gaussian error propagation method (Barrante, 1974). The calculated error is propagated to the porosity estimation. After the percolation experiment, we characterized the core rock sample using the same methodology as before, described in Sect. 2.1.2.

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2.2 X-ray microtomography images

2.2.1 Images acquisition

We acquired the X-ray microtomography images on the ID19 beamline at ESRF (European Synchrotron Radiation Facility), Grenoble (France). The acquisition was done in white beam configuration, using a ROI of 2048 × 1690 pxls. The sample was placed at 1.7 m and different filters were used in this configuration (2.8 mm of Al and 0.35 mm of W) to achieve an energy of 71.1 keV with a gap of 57. The voxel size was $7.42 \mu\text{m}^3$. We acquired 4998 radiographies in 360° , 41 references and 20 dark images to reduce the noise during the 3-D reconstruction. The acquisition time for each radiography was 0.25 s which induces a total acquisition time for the entire sample (two scan steps) of around 1 h (taking the motor movements into account). Two 3-D images were acquired: one for the sample before percolation experiment and one after, respectively named $Bv|_{be}$ and $Bv|_{af}$.

2.2.2 Image processing and parameter extraction

Analysis of the XMT images allows to quantify the volume of the pore structure and detail its distribution. Using the 3-D pore representation, one can estimate its total and connected porosities and its geometrical properties, such as its surface area and pore size distribution. The processed images and results were mostly computed with Voxaya's software. The same methodological framework was applied for each image.

Filtering and region of interest extraction

The very first step in the image processing workflow consists in isolating the region of interest: a cylindrical mask is applied on the image in order to extract its relevant part. A median filter is then used to remove noise while preserving edges of the structures.

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Segmentation and porosity calculation

One of the most important task in image analysis is segmentation. It consists in gathering voxels belonging to a same object and assigning then a single common value. Voxels identified to the matrix constitute the solid phase and have the highest intensity and appear in the brightest gray levels. Pores with size larger than the voxel size (here, 7.42 μm) are entirely captured by the camera and appear in darkest gray levels in the image, forming a phase called void phase or resolved porous phase. We call subresolved porous space the area appearing in intermediate gray levels and formed by matrix (calcite in the present case) and pores of size smaller than the voxel size. Note that this phase is sometimes denoted by the ambiguous term microporous phase whereas resolved porous phase is often called macroporous phase. Presence of pores smaller that the voxel size can be confirmed for example by microscopic observations on thin sections or a priori knowledge of the rock.

In terms of numerical core analysis, computing the porosity requires to determine the relative fraction of the void phase volume and to estimate the pore volume in the subresolved porous space. An image segmentation algorithm based on a region growing method was used to isolate the void phase. An additional image segmentation was then realized to isolate the subresolved porous space and compute its volume fraction in the sample voxel. We can define the sample subresolved porosity Φ_S as:

$$\Phi_S = \xi_x \Phi_x \quad (7)$$

where ξ_x and Φ_x respectively denote the volume fraction and the porosity of the sub-resolved porous space. The total porosity is then given by:

$$\Phi_T = \Phi_R + \Phi_S \quad (8)$$

where Φ_R is the sample resolved porosity (that is, the volume fraction of the void phase). Assuming that the sample is chemically homogeneous, it is possible to estimate Φ_x . We first compute the mean grayscale values corresponding to solid and

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and inscribed in the pore space. Yet, each sphere that is fully included in a larger one have no significant contribution to the pore space geometry and can thus be removed. In other words, this method returns the count of inscribed spheres that are maximal in the sense of inclusion.

5 Geometric parameters

Many geometric parameters can be computed from the segmented image of the pore space, namely the interface surface area, its global curvature and the Euler characteristics (Mecke, 2000; Vogel et al., 2010). Here, we focused on the surface-to-volume ratio sometimes referred as specific surface. Statistical measurements such as chord length distribution functions (Torquato, 2002; Luquot et al., 2014a) were also calculated. The chord length distribution function is linked to a probability density of random chords corresponding to a virtual mean pore diameter depending on each x , y , and z direction. It thus provides information on the sample anisotropy.

Diffusion coefficient

15 Diffusion experiments can be simulated on the void space image following the methodology described in (Sen, 2004). Consider a large number N of (virtual) diffusing particles, initially uniformly distributed in the void phase, and randomly moving following a Brownian motion. The diffusion coefficient $D(t)$ characterizes their ability to disperse in the void phase, probing its structure. Denote by $x_i(t)$ the position of the i th particle at time t and $\sigma(t)^2$ their mean square displacement, that is:

$$\sigma(t) = \frac{1}{N} \sum_{i=1}^N (x_i(t) - x_i(0))^2, \quad (10)$$

Then according to Einstein (1956):

$$\sigma(t)^2 = 6D(t)t \quad (11)$$

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If d_0 denotes the diffusion coefficient in an unbounded domain and τ the tortuosity, then when $t \rightarrow \infty$, $D(t)$ tends to an asymptotic value $D \approx d_0/\tau$.

Skeleton and properties

The skeleton of a three-dimensional object is a one-dimensional reduction, centered inside this object, preserving its geometrical and topological features. It provides a simplified representation of a shape: the skeleton of a cylinder, for instance, consists of its axis of rotational symmetry. Formal definitions can be found in Siddiqi and Pizer (2008).

The skeleton is particularly known to be a tool of great interest to investigate large objects with complex geometry, such as large microtomography images of porous media. An implementation of the classical thinning algorithm described in Lee et al. (1994) was used for this work.

3 Results

The temporal evolution of the increase in calcium concentration, ΔC_{Ca} , during the percolation experiment as well as the inlet and outlet fluid pH are presented in Fig. 1. Dissolution reaction occurred during the percolation experiment. Indeed, the ΔC_{Ca} is always positive ($\Delta C_{Ca} > 0$) indicating Ca release in the outlet fluid. Moreover, the outlet pH (Fig. 1) is higher than the inlet one which corroborates proton consumption and thus calcite dissolution, as described as follow:



Dissolution reaction may induce porosity increase and other geometrical, structural and hydrodynamical parameter changes. Evaluating and characterizing these changes are primordial to develop predictive models of reactive-transport processes such as those occurring for example during CO_2 geological storage, fracking processes, oil and gas exploitation, acid mine drainage or seawater intrusion among others.

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3.1 Laboratory petrophysical parameters

3.1.1 Sample porosity change

Initial porosity measurements on sample Bvl_{be} were performed by the classical triple weighing method (TW) and gives us an initial porosity $\phi_{i(TW)}$ of $16.06 \pm 0.44\%$ (4 measurements), which is slightly higher than the one provided by the quarries miner companies. This porosity is the connected porosity which only takes into account the open pores connected to one of the sample surface. After the dissolution experiments, the porosity was measured by the same methodology four times and we calculated a final porosity $\phi_{f(TW)} = 20.26 \pm 0.73\%$.

Using Eqs. (5) and (6), we performed the mass balance calculation from the dissolution experiments and evaluated the final porosity $\phi_{f(chem)}$ using the initial porosity $\phi_{i(TW)}$ and the ΔC_{Ca} presented in Fig. 1. We obtained a final porosity $\phi_{f(chem)} = 19.37 \pm 0.56\%$ (propagating the error of the TW method on the initial porosity value and the one from the chemical analysis). The slightly higher increase in porosity, measured by the TW method, can be explained by the connection of initial non-connected pores to the new connected porosity by the dissolution process whereas the porosity calculated by the mass balance is affected by the dissolution only. The different porosity measurements and calculations are summarized in Table 1.

3.1.2 Pore size distributions

We obtained the pore-size distribution for sample Bvl before and after the dissolution experiment from the retention curve (RET) as explained in Sect. 2.1.2. We measured the retention curve twice. We first placed the sample in order to apply the centrifuge force in the flow direction of the percolation experiment and then we placed the sample in the opposite direction to evaluate the pore-size anisotropy. If the pore-size distribution was heterogeneous, then we should get different retention curves due to the gradient of the capillary pressure inside the sample. Specifically, large pores at the in-

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let (but not at the outlet) will desaturate at small suctions applied to the inlet (i.e., for small rpm when the inlet is placed outside in the centrifuge). Reversely, if the sample is rotated, those pores will only desaturate when suction is large enough to drain any of the outlet pores. The net result is that the measured curve will exhibit directional dependence as previously observed by Luquot et al. (2014b).

Initially, the pore-size distribution is homogeneous; the initial retention curves are similar in both sample orientations (Fig. 2). After the dissolution experiment, due to calcite dissolution and porosity increase, the retention curves vary from the initial one. Moreover, we can observe in Fig. 2, that after the dissolution experiment, some heterogeneity appeared along the sample inducing different shapes for the retention curves acquired in both directions. The corresponding pore-size distributions are presented in Fig. 3.

We can note that after the dissolution experiment the amount of pores of radii larger than $102.27\ \mu\text{m}$ increases drastically. The increase in largest pore size is similar whatever the sample direction indicating that these pores are well connected together and broke through the sample. We can also observe (Fig. 2) that the second huge difference in the retention curves, between before and after the dissolution experiment, appears for pore radii $10.23 < r_p < 34.99\ \mu\text{m}$ (suction between 5.11 et 17.47 kPa). After the dissolution experiment, less pores of such radii are presented through the sample, indicating that most of the dissolution occurred in these pores.

Moreover, some differences are observed in the pore-size distribution after the dissolution experiment depending on the sample orientation. These differences highlight some heterogeneous dissolution inducing different pore diameter changes along the sample. We can observe that the differences are not so large compared with other experiments with strong dissolution localization (Luquot et al., 2014a). Most of the difference is visible for intermediate and smallest pores ($0.48 < r_p < 10.23\ \mu\text{m}$). Moderately large pores (radius around $10\ \mu\text{m}$, suction at 17.47 kPa) are better connected to the inlet than to the outlet (that is, they drain better when the sample is placed opposite to the flow direction, i.e., dragging toward the inlet, than otherwise). The proportion of

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the smallest pores is consistently smaller when the sample is placed opposite to the flow direction, implying that some dissolution occurred even in these pores at the inlet. However, water contents obtained with the sample placed in the flow direction for high suction (small pore sizes) were slightly higher than before the experiments, implying a small decrease in pore size at the outlet. This mechanism of pore clogging is marginal here.

3.1.3 Diffusion coefficients

Figure 4 displays the results of the two iodide diffusion experiments performed before and after the dissolution experiment on sample Bvl. The curves show the time evolution of iodide at the sink reservoir, which is proportional to the cumulative mass of iodide that has diffused through the sample Bvl until time t . Only the steady-state phase is reported here, when the iodide concentration in the sink cell increases linearly with time. Linear regression of the steady state portion yields the effective diffusion coefficient (Eq. 2). Experimental results are summarized in Table 1. The slope of the iodide increment after the dissolution experiment increases, indicating an increase of the diffusion coefficient. The latter increased by one order of magnitude after the dissolution experiment. This increase is linked to a decrease of the tortuosity coefficient τ from 14.43 (highly tortuous pore skeleton, see Fig. 5) to 3.57. These values of effective diffusion coefficients and tortuosity are coherent with other previous laboratory measurement done on limestone samples (Boving and Grathwohl, 2001; Gouze and Luquot, 2011; Casteleyn et al., 2011; Peng et al., 2012; Luquot et al., 2014b).

3.1.4 Permeability change

The changes in permeability with time $k(t)$ is reported in Fig. 6. Unsurprisingly, permeability increases due to the calcite dissolution process as previously mentioned by other authors (Fredd and Fogler, 1998; Luquot and Gouze, 2009; Noiriel et al., 2009; Elkhoury et al., 2013; Carroll et al., 2013). The permeability increase rate (dk/dt)

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responds to the flow direction during the dissolution experiment). We can observe that both resolved and subresolved porosities increase along the sample length. These porosity increases are homogeneous along the sample except for the first millimeters of the sample where the resolved porosity increase faster than in the remaining part of the sample. The same phenomenon is observed for the subresolved porosity, where its increase is higher in the first 2 mm of the sample. Similar trends of porosity increase due to carbonate dissolution have been monitored by previous authors. Nevertheless, no conclusion on the dissolution patterns can be proposed as Luquot and Gouze (2009) and Menke et al. (2015) linked the homogeneous porosity increase profile to homogeneous dissolution whereas Smith et al. (2013) and Luquot et al. (2014a) observed wormhole formation. These versatile conclusions are due to the complex structure and pore geometry of the different limestone samples used. Visualising 3-D XMT images, we can conclude that during Bvl dissolution experiment a wormhole have been formed promoting a homogeneous porosity increase along the sample.

One of the advantages of using 3-D XMT images is the ability to distinguish the total porosity from the effective one, or in other words from the connected porosity. Performing a connectivity computation, we can evaluate which part of the total porosity is actually contributing to the fluid flow. In Table 3, the volumes of the resolved and subresolved phases are indicated as well as the volume of the connected resolved and subresolved phases with the corresponding fraction of the connected part. We can observe that initially, the sample is mainly connected through the subresolved phase, but after the dissolution experiment the resolved porous phase becomes more connected and mostly contribute to the fluid pathway. This increase in connectivity through the resolved porous phase can be linked to the wormhole formation which represents 71.47 % of the connected resolved porous phase. Various other small clusters compose the percolating resolved phase but none of them is higher than 2 % of the total porous volume. The main connected path after the dissolution experiment is imaged in Fig. 5.

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3.2.2 Pore size distributions

Calculation of the pore size distribution was conducted on the resolved porous phase on sample Bvl_{be} and Bvl_{af} using two different methodologies. We calculated the pore size distribution (Psd) as explained in Sect. 2.2.2, computing the radius of the largest inscribed sphere centered at every point of the pore space, provided it is maximal for inclusion. We also estimate an equivalent pore size distribution performing statistical measurement and calculating the chord length distribution functions (C-I). The chord length distribution functions for sample Bvl_{be} and Bvl_{af} are plotted in Fig. 8 for the 3 directions (x , y , z). Results from both methodology (Psd and C-I) are summarized in Fig. 3 where the pore volume distribution is scaled according to the experimental RET thresholds.

In Figs. 3 and 8, we can observe that initially, the sample is mainly composed of pores having small and intermediate diameters. Most of the pores are smaller than $204.5 \mu\text{m}$ (69.73 %) in diameter and no anisotropy is observed. After the dissolution experiment, the chord-length distribution evolved and a certain anisotropy appears. In sample Bvl_{af} , the amount of small to intermediate pores diameter decreased significantly to 11.27 % of pores smaller than $204.5 \mu\text{m}$ in diameter. Larger pores were formed due to the dissolution process. Significant amounts of pores with diameters comprised between 1 and 3 mm are measured and up to 20 mm (core sample diameter) in the x direction which corresponds to the local face dissolution at the sample inlet inducing large porosity increase (Figs. 7 and 5).

The pore size distribution (Psd) presents similar results than those obtained by the chord length function. Some discrepancies are observed for sample Bvl_{be} for the largest pore diameter. With the Psd measures, the highest pores have a diameter comprised between 70 and $204.5 \mu\text{m}$, whereas with the chord length function, we calculated initially lower proportion of these pores and a higher one for the largest pores (diameter higher than $204.5 \mu\text{m}$).

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3.2.3 Diffusion coefficients

The effective diffusion coefficient $D_{\text{eff(XMT)}}$ before and after dissolution is obtained by computing randomly distributed particles in the rock pores following the method describe in Sect. 2.2.2. Figure 9 displays the results of the two computations performed on Bvl_{be} and Bvl_{af} . The curves show the mean squared displacement (Msd) for an interval time step i . For large time steps, the Msd is linearly dependent to the effective diffusion coefficient (Einstein, 1956). Linear regression of the steady state portion yields the effective diffusion coefficient. The obtained effective diffusion coefficient for Bvl_{be} and Bvl_{af} are summarized in Table 1. As expected and previously reported in the literature (Gouze and Luquot, 2011; Luquot et al., 2014b), the effective diffusion coefficient increases after limestone dissolution experiments.

4 Comparison and discussion

Here we compare different parameters characterized using, on the one hand, classical laboratory measurements and on the other hand, XMT images. Before considering these parameters, we compared laboratory measurements and computational analyses durations for each parameter, in order to evaluate which approach is the most time consuming. All image processing described in Sect. 2.2.2 have been performed on a workstation equipped with two quad core Intel Xeon CPU X5560 @2.80 GHz and 192 GB DDR3 RAM. We can observe in Fig. 10 that globally, even if the computer used here is not a high end build, the total analysis time for Bvl_{be} and Bvl_{af} is much shorter using images processing than performing laboratory measurements. The total time needed to extract the different parameters discussed in this article from the XMT images is 23 days, whereas the time required to determine the same parameters using laboratory measurements is 60 days. Moreover, some specific processing (namely skeletonization) were performed using basic, non-optimized implementations of classical algorithms that can be found in open source software packages such as

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ImageJ. Besides, in most cases, data extracted from XMT images provided more information than the desired parameters studied in this article. Considering porosity for instance, only effective porosity can be determined by the experimental triple weighing method, whereas both effective and total porosities can easily be calculated from the XMT images. Total porosity can be a key parameter when chemical processes such as dissolution occurred. The final porosity closely depends on the initial effective porosity, the porosity created by dissolution and part of the initial closed porosity that the dissolution process made accessible.

Nonetheless, the main drawback of the XMT image analysis is the high dependence on the voxel size for all parameters. When using different laboratory techniques to measure the desired parameters, various resolution scales can be achieved. For example, the total fluid–rock interface determined by BET measurement has higher resolution than the one determined by XMT images. Specifically, the grain roughness as well as grains smaller than the XMT resolution (7.42 μm) cannot be measured and the water–rock interface area is a priori underestimated.

Nevertheless, for most of the determined parameters, good agreement is observed between the processed data acquisition and the one measured experimentally. As observed in Table 1, the initial porosity determined by the triple weighing method is much closer to the effective porosity measured from XMT images. We indeed calculated a 0.74 % difference. After the dissolution experiment, the estimated porosity is quite similar even if the difference is more important. The final porosity determined by the mass balance calculation is the lowest one ($\phi_{\text{f(chem)}} = 19.37 \pm 0.56 \%$). As explained before, the slight difference between the porosity obtained by triple weighing and mass balance calculation can be explained by the connection of initially non-connected pores to the new connected porosity by the dissolution process. Actually, the porosity calculated by the mass balance is only affected by dissolution. In this case, if only initial effective porosity and mass balance are used, the final porosity can be underestimated. The porosity measured by the triple weighing method is smaller than the one estimated from the XMT images. This difference can be due to the formation of highly connected

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smallest ones. It might be interesting to simulate drainage and imbibition experiments using the XMT images as previously done by Knackstedt et al. (2006) and Prodanovic et al. (2010) in order to compare the laboratory RET measurements in a further study. To summarize, the pore size distribution obtained by the retention curves, indicates the capillary pressure needed to extract a specific fluid volume but without any information about the amount of pores containing this fluid volume and the respective pore diameters. The two other methods used here to extract the pore size distribution using the XMT images allow to determine the pore size diameter at each voxel point with some anisotropy information (C-I technique). Nevertheless, with these two methods, we don't have any knowledge about the connectivity and the accessibility to these pores. Using the extracted skeleton, we can extract both pore and throat distribution and localize them in the 3-D sample. This fourth method gives the best pore and throat size distribution and their localization (Fig. 5).

The third main parameter measured here is the effective diffusion coefficient. By laboratory through diffusion experiments, determination of the diffusion coefficient is time consuming (Fig. 10) and strongly depends on sample length as the diffusion time increases with the squared length. Using the XMT images, the calculation of the effective diffusion coefficient is very efficient and performed in less than 9 min. The results of both methods are presented in Table 1. With both techniques, the effective diffusion coefficient increased after the dissolution experiment by one order of magnitude. Moreover, the values obtained by laboratory measurements and statistical modeling are similar. The statistical estimation using XMT images is a good option to determine the effective diffusion coefficient as the time needed is 1500 times faster than performing laboratory through diffusion experiments.

5 Conclusions

In this paper, we have shown that microtomographic imaging hardware and computational techniques have progressed to the point where properties such as effective

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diffusion coefficient, conductivity and pore size distribution can be calculated on large three-dimensional digitized images of real core rock sample. We demonstrated that for most of the parameters studied here, the values obtained by computing XMT images are in agreement with the classical laboratory measurements. For some parameters, such as the porosity, the computational one is the more informative, as one can calculate both total and effective porosity. As discussed here, when dissolution process occurs, the knowledge of the total porosity can be necessary. As the definition of pore is highly discussed in the scientific community, we observed that the pore size distributions obtained by XMT images and laboratory experiments are slightly different. We highlighted advantages and limitations of both approaches: the RET measurement allows to determine the accessible volume for a given capillary pressure, whereas Psd and C-I methods extract the maximum pore volume locally without information of its accessibility. Concerning the effective diffusion coefficient, we observed that both approaches are valuable and similar results are obtained. Nevertheless, the duration of a laboratory through-diffusion experiment is much longer than the time required by the computational option (about 1500 times longer).

As a conclusion, computing XMT images to determine transport, geometrical and petrophysical parameters provide similar results than the one measured at the laboratory in only 23 days instead of 60 days for the laboratory option.

Furthermore, new developments are expected in a near future favouring microtomographic imaging at higher resolutions with faster acquisition times allowing dynamical effects to be imaged, Bultreys et al., 2015; Douissard et al., 2012; Landry et al., 2014. Moreover, further developments using the extracted skeleton will allow to extract the accessible pore volume and the capillary pressure needed to ingress.

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Table 3. Resolved (RPV) and total (TPV) phase volume [mm^3] and connected resolved (connected-RPV) and total (connected-TPV) phase volume [mm^3] with the respective connected resolved (connected-RF) and total (connected-TF) fraction [%].

	RPV (mm^3)	connected-RPV (mm^3)	connected-RF (%)	TPV (mm^3)	connected-TPV (mm^3)	connected-TF (%)
Bv_{be}	1007.76	380.90	37.80	1856.53	1727.78	93.07
Bv_{af}	1511.34	1080.18	71.47	2432.96	2321.12	95.40

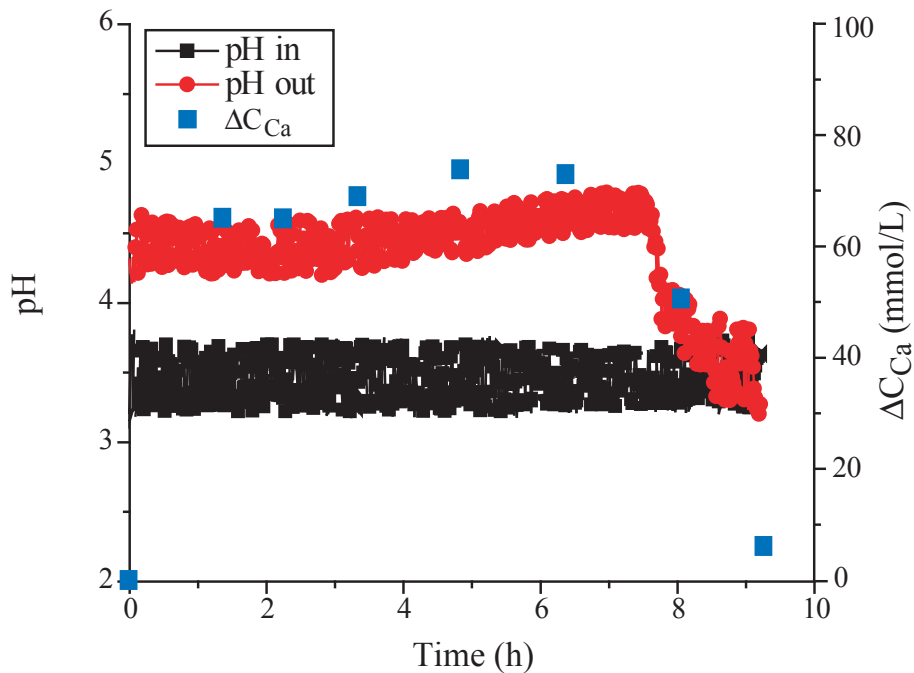


Figure 1. Inlet (black) and outlet (red) pH variation during the percolation experiment as well as variation in calcium concentration(blue).

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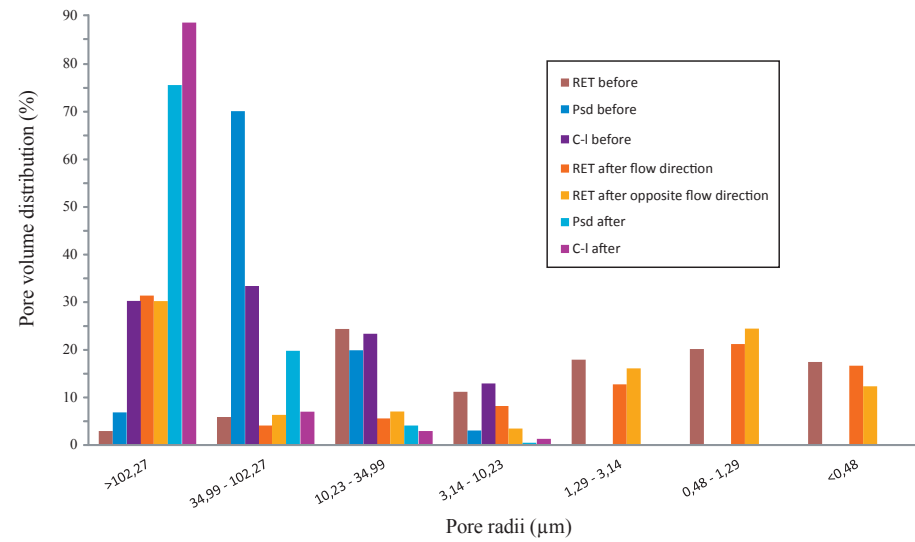


Figure 3. Pore volume content for different pore size diameters before and after the dissolution experiment. The data have been extracted from the Psd and C-I numerical measurements and RET laboratory acquisition. For the latter, the distributions after dissolution were obtained both by draining in the flow direction and in the opposite direction.

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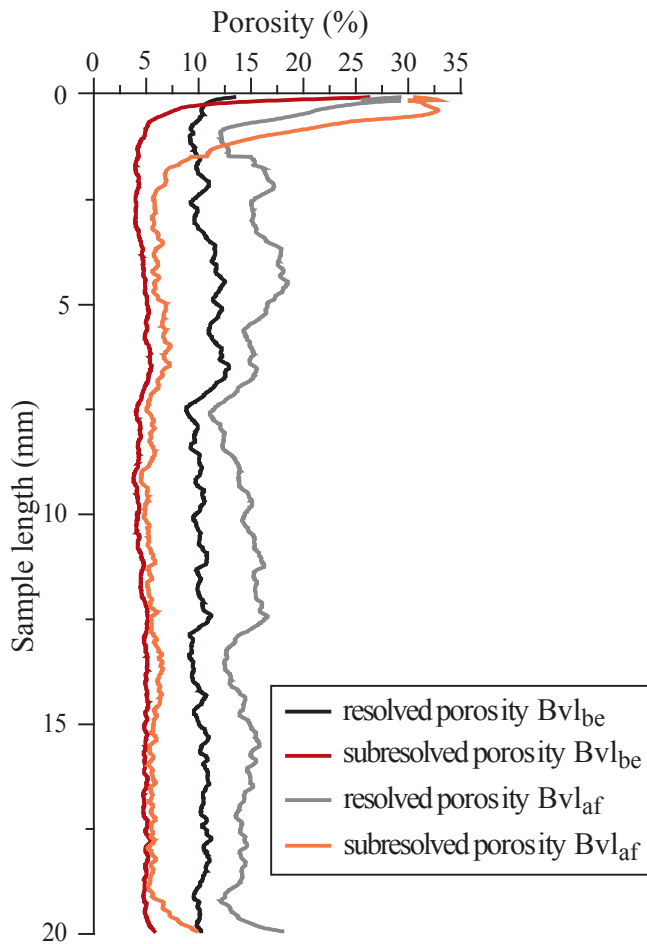


Figure 7. Porosity changes along samples Bvl_{be} and Bvl_{af} . Both resolved and subresolved porosities are plotted.

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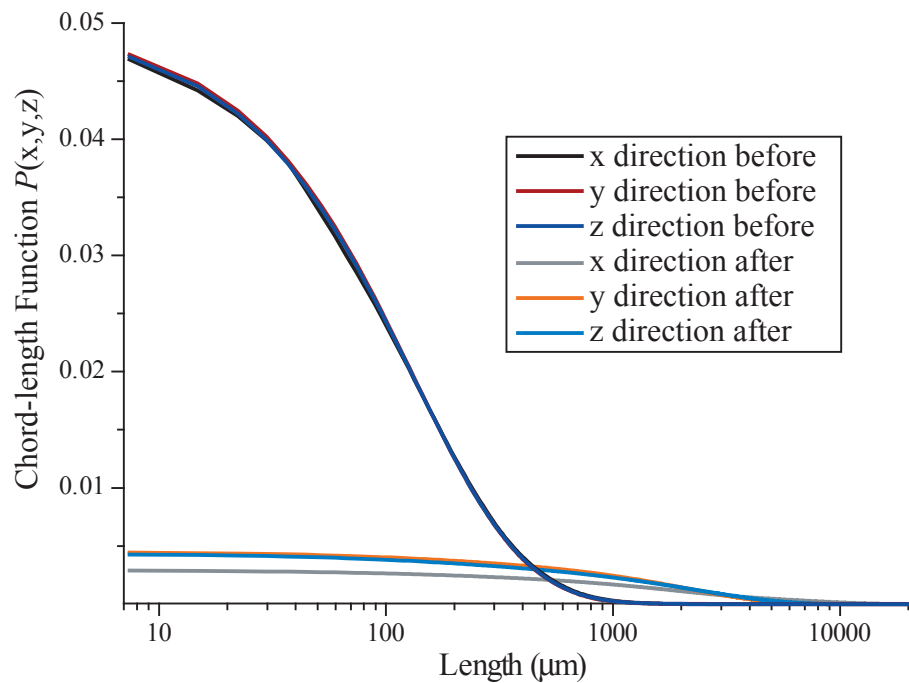


Figure 8. Chord length function along x , y and z ($P(x, y, z)$) for sample BVI before and after the dissolution experiment.

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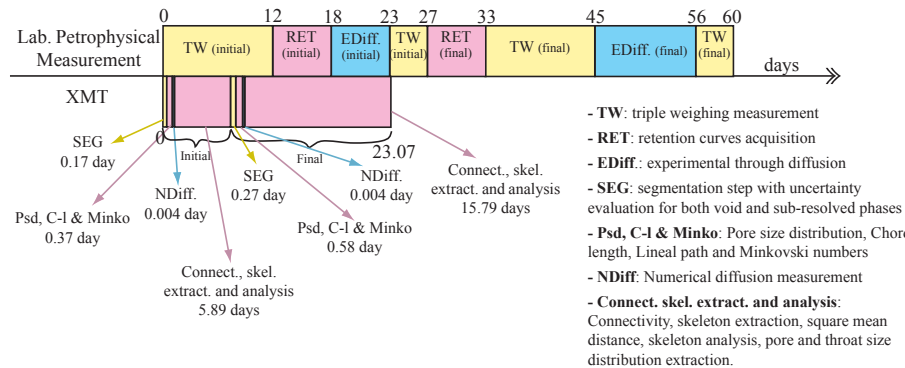


Figure 10. Time scale of the different methods used in this study for both laboratory and XMT images approaches.

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