Introduction
Imaging techniques are becoming ever more valuable tools to characterize the microstructure (especially in three dimensions), while numerical models to calculate transport properties based on experimental images of the microstructure are quickly maturing (Bultreys et al., 2015, 2016). Several digital image analysis (DIA) methods have been proposed to evaluate the petrophysical and geometric properties the pore system in two-dimensional (2D) and identify the macro and mesopores (Neto et al., 2018; Da Rocha et al., 2019). Porous network modelling, thus, is one of the primary means of simulating the hydraulic behaviors of porous media at the micro-scale level. Network models, that represent the void space of a rock by a lattice of pores connected by throats, can predict several properties petrophysics (Dong and Blunt, 2009). The predictive value of network models depends on the accuracy of imaging and, the correspondence of network, via real porous rocks (Sok et al., 2002; Sheppard et al., 2004). The improvement of conventional network modelling approaches to study carbonates, have been discussed, recently, in many studies. It was development a multiscale imaging methodology, to better account for the pore structure and connectivity in carbonates, where pore space registration was used to combine three-dimensional (3D) and 2D images using microcomputed tomography, focused ion beam, and backscattered scanning electron microscopy (Bernabé et al., 2010; Raoof and Hassanizadeh, 2010; Sok et al., 2010; Gharbi and Blunt, 2012; Rabbani et al., 2014).

Ioannidis and Chatzis (2000) presented a dual network model, which considers interconnected channels in vuggy carbonates, overlapping vugs in the matrix block. They compared the model's predictions with capillary pressure measurements. Dong and Blunt (2009) compared four different methods of network extraction and reconstruction in 3-D images of sandstone and carbonate: medial axis, based on speed, grain recognition and maximum ball algorithms. For wet water cases, the predictions of relative permeability for flooding showed similar behavior to carbonates. They concluded that, generally, maximum ball extraction and velocity-based algorithms provide similar predictions of multiphase properties.

Raoof and Hassanizadeh (2010) developed a new method to generate a network of multidirectional pores to represent a porous medium. The method is based on a regular cubic network, which has two elements: pore bodies located at the regular lattice points and pore throats that connect the pore bodies. This method showed good agreement between the results of the simulation and the observation data on the distribution of coordination numbers and other network properties, such as the number of pore bodies and pore throats and the average coordination number.

Van der Land et al., (2013) demonstrated how scale models of pores, representing typical carbonate sediment and their diagenetic histories, can be used to quantify the evolution of petrophysical properties in carbonate rocks. When 3D pore architecture models (ie, the spatial distribution of solids and pores) were generated from 2D binary images, they represented the typical textural changes of carbonate sediment following diagenetic pathways.

Bultreys et al., (2015) developed a new model of double pore network based on micro-computed (micro-CT), based on pore network (DPNM), which considers microporosity in a sophisticated way using symbolic elements of called micro-links while treating macroporosity as a traditional model of pore network. The connectivity and conductivity of the microporosity are derived from local information measured in micro-CT scans. Microporous connectivity is allowed both in parallel and in series to the macropore network.

To interpret and simplify 2D digital image analysis data sets, the main challenge is to determine which empty space is exactly pore or throat. Although the continuous and integrated void space of the porous media is not part of different pores and throats, it is necessary to make some simplifying assumptions (Rabbani et al., 2014).

This article presents a computational algorithm for automatic extraction of resources from the pore network that can present the realistic structure of pores and pore throats, based in Rabbani et al., (2014) studies. In this method, the pores and throats are directly detected and separated by the coupling of two well-known image processing algorithms known as distance function and watershed segmentation of 2D image obtained from samples of pre-salt carbonate reservoirs in the Santos Basin, Southeastern Brazil.
Method
Initially, 2D digital images are imported and then converted to a grayscale image. This process converts RGB images to shades of gray, while eliminating hue and saturation information and maintaining luminance. A binary image is created, from the grayscale image, by replacing all values above a globally determined limit by 1s and setting all other values to 0s.

To digitize porous spaces, binary images are used, and each segment of porous media is converted into a binary map that contains 1 for grains or solids and 0 for pores or voids (Maurer et al., 2003). By default, the binarize algorithm uses the Otsu method, which chooses the threshold value to minimize the intraclass variance of the limited black and white pixels (Kim et al., 2020).

After the binarization process, the watershed algorithm was used, which returns a matrix of labels where it is possible to identify the watershed regions of the input image, which can have any dimension. Watersheds find "catchment basins" or "lines of ridges of the river basins" in an image, treating it as a surface where pixels of light represent high elevations and dark pixels represent low elevations.

The elements of are integer values greater than or equal to 0. The elements labeled 0 do not belong to a single watershed region. The elements labeled 1 belong to the first region of the watershed, the elements labeled 2 belong to the second region of the watershed, and so on. By default, the watershed uses neighborhoods connected to 8 to image 2D inputs (Liu et al., 2017; Singh et al., 2021).

The number of coordination or connectivity of the pore network is easily obtained by analyzing the pores and throats and counting the number of throats connected to each pore. Porous connectivity is one of the most important parameters determining the hydraulic characteristics of the porous medium.

The images are segmented in the pore and a topologically representative network of pores, then, the pore throats are extracted from these images. The distance function calculates the distance between each pixel in the empty space of the porous media and the closing per pixel occupied by the solids. The distance function occurs in four different ways to generate contour lines or planes: a) Euclidean, b) City block, c) Chessboard, d) Quasi-Euclidean (Rosenfeld and Pfaltz, 1966; Rabbani et al., 2014; Kumar and Anuradha, 2017).

Results
For test the accuracy of the algorithm implemented for porous media segmentation was used a sample of carbonate reservoir of Brazilian pre-salt (Figure 1). This sample corresponded a laminate which presents as the most striking diagenetic characteristic the process of dissolving matrix (micritic) and replacing matrix (micritic) by quartz, which causes the appearance of secondary porosity, of the types intercrystalline, interparticle and intraparticle. It also has incipient lamination characterized by the presence of bioclasts and organic matter. The porosity obtained in the laboratory (helium) is 8.6% and the permeability is 0.91 mD.

Figure 1. Carbonate reservoir sample, Brazilian pre-salt.

Figure 2. Comparison between a 2D sample thin section real, gray, binarized and segmented image.
Figure 2 shows the process of digital analysis of 2D image applied to a thin section of rock with the dimensions of 491 x 398, obtained with 5X magnification and 8-bit resolution. It is possible to observe the real image, the grayscale image, the binary image and the segmented image respectively (Figure 2). In the heterogeneous sample of carbonate studied, after the segmentation process, it was possible to analyze its pore network. The analysis of the number of sample coordination is reliable and is in accordance with the Watershed method proposed by Rabbani et al., (2014), as can be seen by the actress plot of the sparse adjacency matrix of 1811 points of the graph of connectivity. In addition, to detect pore connectivity, the histogram of the coordination number distribution frequency was plotted, where it is possible to observe a concentration of pores with three connections (Figure 3).

There are four different types of distance functions, as shown (Figure 4). In this research, it was found that the Chessboard is the best type of distance feature to differentiate between pores and rock throats. It is also possible to note that the Quasi-Euclidean function showed satisfactory results, but not the best for the purpose of this study. The best forms create angular and cubical contours which intersect with curved pore walls in explicit boundaries, leading to a stronger and clearer distinction between the pore-throat.

Figure 3. Segmented image, connectivity graph of the sparse adjacency matrix and histogram of the distribution of the coordination number.

Conclusions
The realization of a segmentation of digital images, using a watershed algorithm, showed its effectiveness, in this study, in the detection of throats and, therefore, in the differentiation of pores. It was created a clear and simple pore network model, taking the pores as spheres and, the pore throats as cylinders. The workflow developed, using known image processing functions, allowed us to estimate, with satisfactory results, petrophysical properties intrinsic to the pores. Finally, the degree of coordination estimated with this method is in accordance with the results found in the literature.

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References


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