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Estimating hydraulic parameters of the Açu-Brazil aquifer using the computer analysis of micrographs

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SUMMARY

The conventional way of obtaining hydraulic parameters of aquifers is through the interpretation of aquifer tests that requires a fairly complex logistics in terms of equipment and personnel. On the other way, the processing and analysis of digital images of two-dimensional rock sample micrographs presents itself as a promising (simpler and cheaper) alternative procedure for obtaining estimates for hydraulics parameters. This methodology involves the sampling of rocks, followed by the making and imaging of thin rock samples, image segmentation, three-dimensional reconstruction and flow simulation. This methodology was applied to the outcropping portion of the Açu aquifer in the northeast of Brazil, and the computational analyses of the thin rock sections of the acquired samples produced effective porosities between 11.2% and 18.5%, and permeabilities between 52.4 mD and 1140.7 mD. Considering that the aquifer is unconfined, these effective porosity values can be used effectively as storage coefficients. The hydraulic conductivities produced by adopting different water dynamic viscosities at the temperature of 28 °C in the conversion of the permeabilities result in values in the range of $[6.03 \times 10^{-7}, 1.43 \times 10^{-5}]$ m/s, compatible with the local hydrogeology.

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1. Introduction

The knowledge of the porosity and permeability petrophysical properties at a given region is of fundamental importance to the study of its hydrogeological behavior. More accurate estimates of these properties can help us to have a better understanding of the hydraulic behavior of aquifers, thus contributing to a optimized management of underground water resources.

Traditionally, to obtain these parameters, one would have to interpret aquifer tests, usually with the help of specific software. This task incurs in analyzing data related to the changes of water levels in the production and observation (piezometer) wells, through time, as a response to the pumped flows. Additionally, one could estimate values for some of these parameters by performing laboratory tests on rock samples of the aquifer, using equipment such as porosimeters and permeameters. Additional information, such as the thickness of the aquifer layer, the temperature and water dynamic viscosity of the formation are needed in the case of the acquisition of values of hydraulic conductivity from the intrinsic permeability and hydraulic transmissivity. Uncertainties in these measurements could be credited initially to the heterogeneous characteristics of the geological and hydrogeological medium (Nilsson et al., 2006). Younger (1992) showed that there is a positive correlation between permeability values obtained from estimates of thin rock sections and values obtained from permeameters. These hydraulic conductivities, obtained from the analysis of thin rock samples, however, were estimated through direct relation between porosity and conductivity reported by Marsily (1986).

The analysis of porous media using digital images consists of a fairly recent approach, and it aims to describe and simulate important rock properties through computational experiments over complex scientific models. This methodology can be employed by either using micro-CT three-dimensional reconstructions, such as was done by Blunt et al. (2013) or by analyzing two-dimensional (2D) images (Coskun and Wardlaw, 1993).

The usage of micro-CT in petrophysical analysis has increased in the last three decades. This technique is very useful in analyzing the structure of rocks as well as estimating their porosity and

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permeability. However, in order to acquire images with high resolution and signal to noise ratio, one needs to use high energy X-ray sources, such as a synchrotron X-ray source, that are expensive and of limited accessibility, or using more advanced, high-performance micro-CT (Baker et al., 2012; Cnudde and Boone, 2013). This later type, however, requires high scanning times, in the order of a few hours (Brunke et al., 2008), depending on the size and heterogeneity of the micro-core and the scanner characteristics.

Therefore, techniques that employ the analysis of 2D images of rock samples present themselves as a more accessible alternative in terms of cost and required equipment in the estimation of hydrogeological parameters. This type of approach was originally developed for oil reservoirs (Adler et al., 1990; Coskun and Wardlaw, 1993; Gaspari, 2006; Gasperi, 1999; Santos et al., 2002a), and consists of obtaining quantitative information and identifying microstrutural patterns, by analyzing two-dimensional micrograph images (thin sections of aquifer rocks). The combination of these data through correlation or multivariate regression allows the prediction of several petrophysical properties, including porosity and permeability (Berryman and Blair, 1986; Eberli et al., 2004; Kameda, 2004; Ruzyla, 1986; Santos et al., 2002a; Schaap and Lebron, 2001). The analysis of these images involves the characterization of the porous media, evaluating the inter-connectivity between pores, their geometry, as well as the size and distribution of constituents in the solid phase of this porous system. The estimation of these factors can additionally involve the assemblage of a three-dimensional network with different pore connectivity models and distribution of constituents (non-porous areas), allowing the estimation of permeability values through the flow simulation in the porous media (Liang et al., 1998; Santos et al., 2002a; Talukdar et al., 2002).

In this context, this article presents an estimation of storage coefficients, associated with effective porosities and permeabilities, using a methodology based on the analysis of two-dimensional micrographs of thin rock sections of an aquifer formation. We chose this approach due to the less expensive and more accessible nature of it.

The hydrogeological target of this study is the outcropping portion of the Açu aquifer (homonimous formation) of Cretaceous age and situated in the central-south portion of the Potiguar basin, in Brazil (see Fig. 1).

2. Geological and hydrogeological context

The Açu Formation, together with the superimposed Jandaíra formation (of predominantly carbonate nature), compose the Apodi part of the Potiguar basin, that is situated in the northern region of the Rio Grande do Norte state (RN), in the northeast of Brazil, as can be seen in Fig. 1. This basin was formed by the rifting process along the Brazilian coast, through the separation and drift of the South American and African continents that started at the end of the Jurassic Period. Its tectonic-structural conditioning happened, initially, from NW distentional efforts (in relation with the current positioning of the South American continent), with a posterior transcurrent/transformant dextral *E–W* regime, associated with the development and evolution of the Brazilian equatorial coast starting in the late Barremian or the Aptian (Angelim et al., 2006; Ferreira et al., 1998; Matos, 1992).

Lithologically, the Açu formation is formed, predominantly, from thin to coarse sandstone of whitish to reddish coloring, although it can have intercalations of shale and claystone, besides conglomerate levels, associated with a fluvial depositional system and having thicknesses of up to 1000 m (Angelim et al., 2006; Vasconcelos, 2006). Its outcropping portion, target of the current study, represents an approximately continuous strip in the *E–W* direction, at the south border of the Potiguar basin (Fig. 1), extending from the Ceará state (CE) to the vicinity of the city of João Câmara (RN).

The Açu aquifer, of the homonym formation, represents the main subterranean hydraulic reservoir of this region of Rio Grande do Norte and of the Potiguar basin. Its outcropping portion, lithologically represented by medium-graines sandstones, presents an unconfined aquifer (Melo et al., 2005; Stein and Melo, 2006). The flow of its wells increase in the north direction, going from about 10 m^3/h at depths deeper than 100 m, close to the crystalline terrains at the southern limit of the formation, to flows above 100 m^3/h at depths shalower than 120 m close to the northern limit of the formation (Melo et al., 2005; Stein and Melo, 2006; Vasconcelos, 2006).

Hydraulic parameters of the Açu aquifer are somewhat scarce. By performing aquifer tests and interpretation using the simplified Jacob's method (Custódio and Llamas, 1983; Feitosa et al., 2008), Melo et al. (2005) shows hydraulic conductivity values of

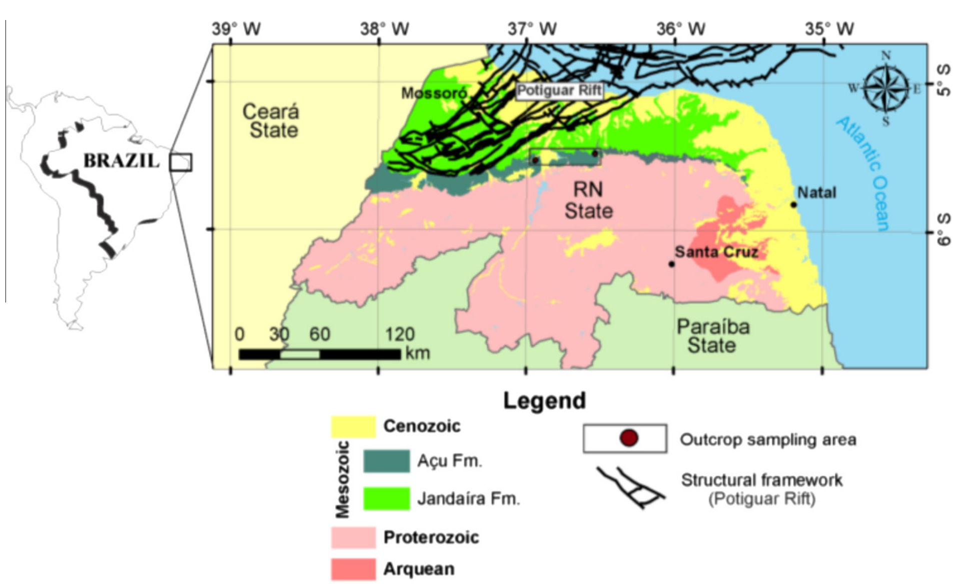

Fig. 1. Location of the study area and regional geological contextualization of the outcropping portion of the Açu formation and aquifer, at the south border of the Potiguar basin, highlighting the visited area (adapted from Angelim et al. (2006)).

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