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Pore network quantification of sandstones under experimental CO_2 injection using image analysis

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ABSTRACT

Automated-image identification and quantification of minerals, pores and textures together with petrographic analysis can be applied to improve pore system characterization in sedimentary rocks. Our case study is focused on the application of these techniques to study the evolution of rock pore network subjected to super critical CO_2-injection. We have proposed a Digital Image Analysis (DIA) protocol that guarantees measurement reproducibility and reliability. This can be summarized in the following stages: (i) detailed description of mineralogy and texture (before and after CO_2-injection) by optical and scanning electron microscopy (SEM) techniques using thin sections; (ii) adjustment and calibration of DIA tools; (iii) data acquisition protocol based on image capture with different polarization conditions (synchronized movement of polarizers); (iv) study and quantification by DIA that allow (a) identification and isolation of pixels that belong to the same category: minerals vs. pores in each sample and (b) measurement of changes in pore network, after the samples have been exposed to new conditions (in our case: SC–CO_2-injection). Finally, interpretation of the petrography and the measured data by an automated approach were done.

In our applied study, the DIA results highlight the changes observed by SEM and microscopic techniques, which consisted in a porosity increase when CO_2 treatment occurs. Other additional changes were minor: variations in the roughness and roundness of pore edges, and pore aspect ratio, shown in the bigger pore population. Additionally, statistic tests of pore parameters measured were applied to verify that the differences observed between samples before and after CO_2-injection were significant.

1. Introduction

Automated identification and quantification of mineral phases, textures and porosity are important tools for petrographic characterization of rock samples. Despite the conventional qualitative mineralogy-texture studies performed by optical and SEM microscopy techniques, a more detailed understanding of the rock properties (mineral/pore areas, perimeters, etc.) is desirable in some geological studies. This requires a quantitative petrography procedure which is the object of this contribution. Quantitative assessment of petrography is an essential part of geosciences works as it provides a key to the successful interpretation of rock texture and mineralogy (Higgings, 2006).

Image analysis represents an important advance over traditional techniques (point counting) to automate the characterization of objects in digital-images (Berrezueta and Castroviejo, 2007; Castroviejo et al., 2002; Ehrlich et al., 1984; Grove and Jerram, 2011; Pirard et al., 1999; Russ, 1992). Measurements made from 2D sections, which form the basis of this work, record the porosity as resolvable from an optical image of the sample (total optical porosity).

Nevertheless, application of image analysis in automated identification of mineral phases in images taken from a petrographic microscope has limitations (Fabbri, 1984; Launeau et al., 1994; Petruk, 1989; Pfleiderer et al., 1992; Starkey and Samantaray, 1993). The main problem is that in plane-polarized light (PP) many minerals are colorless, whilst in cross-polarized light (XP) the interference color depends on a variety of factors in addition to mineral type (Fueten and Mason, 2001). However, these circumstances are partially overcome, using a rotating polarizers stage specifically designed as an addition to standard optical-microscope, allowing the thin section to remain fixed while the polarizers are rotated (Fueten, 1997; Thompson et al., 2001). A simplified method of rotating polarizer stage was applied by Tarquini and Favalli (2010) for petrographic analysis. They used images of

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thin sections acquired under 4 directions of polarization (each 22.5°) together with an image without polarization. This approach enhanced the use of standard image processing techniques on thin sections for the segmentation, measurement and mineral identification.

According to Shapiro and Stockman (2001) and Martínez-Martínez et al. (2007), image segmentation is the process of partitioning a digital-image into multiple segments (sets of pixels) and involves identification and isolation of pixels that belong to a same category. Mineral grains identification by DIA is usually achieved by segmentation based on edges (Goodchild and Fueten, 1998; Heilbronner, 2000; Lumbreras and Serrat, 1996; Starkey and Samantaray, 1993), regions (Faugeras and Hebert, 1983; Medioni and Parvin, 1986) or combination of both (Pavlidis and Liow 1990; Zhou et al., 2004).

Nowadays some image processing tools are based on methods originated from the fields of pattern recognition and artificial intelligence. The accuracy of the automatic image segmentation methods has been severely compromised by the presence of shared edges of grains, despite the large number of distinct strategies like: (a) seed region growing (Choudhury et al., 2006), (b) Level Sets (Lu et al., 2009), partial differential equations (Lu and Ning, 2010), cellular automata (Gorsevski et al., 2012) and image foresting transform (Mingireanov Filho et al., 2013).

The identification and classification of porous system based on image analysis of thin sections represent a simple task compared to the difficulties for identification of anisotropic minerals (e.g. color changes or birefringence properties). The described method is based on distinguishing the pore-network from the mineral-network attending their mineralogical and petrographic characteristics, paying particular attention to the possibility that in some cases pore and mineral can show similar appearances. The segmentation of the porous system is made by regions, applying the “thresholding” segmentation method (based on threshold values to turn a raw image into a binary one, the pixels being partitioned are dependent on their intensity value). In this way we can quantify the evolution of small changes in the configuration of pore network.

In this present paper, the application of DIA (Digital Image Analysis) is focused on quantifying changes in the pore system of sandstones before and after being exposed to supercritical CO_2 (SC–CO_2). Deep geological storage into rock porous formations is considered the most appropriate strategy for CO_2 sequestration (Benson and Cole, 2008; Gauss, 2010; Izeg et al., 2008) and injectivity is a technical key and economic issue for Carbon Capture Sequestration projects (Bacci et al., 2011). The viability of the CO_2-injection depends mainly on the porosity and permeability of storage rocks. Our research (Berrezueta et al., 2013) consisted of experimental injections of SC–CO_2 into rocks which are representative of potential storage reservoirs in Spain. The main result obtained was that physical and/or chemical changes due to CO_2 injection induce textural readjustments resulting in an increase of the micro porosity of the storage rocks. These studies allowed a mineralogical interpretation of variations in the pore system and the development of a conceptual model for the evolution of the textures. This work was therefore aimed at the mineralogical and petrography study of the rocks before and after CO_2 injection and special care was put into the development of a model to explain the changes observed. DIA techniques were used to monitor the changes, although we had not established the full procedure in detail.

In the following sections, data acquisition methods and automated identification of porosity will be described and explained in detail. The application of the method proposed has permitted us to quantify the porosity changes occurred when rocks interact with CO_2 at supercritical conditions.

2. Materials and methods

2.1. Samples selection

Sampling of sedimentary rocks suitable for CO_2-injection was carried out in order to study the quantification of its pores. Two contiguous blocks were collected from the homogeneous sample and two from the heterogeneous one. One of each distinct sandstone blocks was subjected to experimental tests upon which CO_2 was injected to supercritical conditions and kept within the sample during ≈ 1000 h at P–T conditions of 75 bars and 35 °C (see Berrezueta et al. (2013) for details). The four block samples (two before and two after the experimental injections) were studied by optical and SEM microscopy to qualitatively monitor the textural and mineral changes by thin sections (30 μm thick) made in the contiguous part of the blocks.

The quantification of porosity changes in the untreated and CO_2-treated was initially attempted by point counting. This method did not show significant changes, probably due to the error of the technique. Furthermore, Hg-porosimetry technique was used to quantify the pore volume. This technique did not show changes in the pore volume, between the pre-CO_2 injected and post-CO_2 injected samples. Thus, pore network changes identified by optical and SEM microscopy were attempted to be quantified by DIA establishing a systematic protocol.

The performance of DIA process was evaluated comparing the errors between DIA and point counting techniques. The sources of error could be (a) errors as a result of systematic observations of a thin section (counting error): result of counting observations being an estimate of the true area and not the true fraction. (b) The user introduced variability (operator error): result of misidentification, inconsistent identification, mistakes. (c) The error encountered when using a 2D slice to estimate volume percentage in the hand sample (specimen error), in our study this error was equivalent for DIA and point counting techniques as we used the same samples. The errors due to systematic observations (counting errors) and the interoperator variability (operator error) in point counting and DIA have been sourced from the literature (Chayes and Fairbairn, 1951; Demirmen, 1971; Galehouse (1971); Griffiths and Rosenfeld, 1954; Grove and Jerram, 2011). For point counting, Grove and Jerram (2011) calculated counting errors to 95.4% confidence level (2σ) counting five hundred points for each thin section (10 operators, 14 thin sections, and measuring porosity area) produced counting errors of 2.55%. Chayes and Fairbairn (1951) using 5 operators, 10 thin sections and measuring quartz area calculated a counting error of 2.6%. Grove and Jerram (2011), taking into account the DIA pore area analysis on thin sections (10 operators, 14 thin sections, and measuring porosity area), calculated counting errors of 0.039 (area %). In the case of operator error (1σ) for point counting Chayes and Fairbairn (1951), using 5 operators, 10 thin sections and measuring quartz area calculated an operator errors of 2.5% of area. Griffiths and Rosenfeld (1954) using 5 operators, 3 thin sections and measuring quartz area calculated an operator error of 1.2%. Demirmen (1972) (using 8 operators, 5 thin sections and measuring limestone constituent's area), calculated an operator error of 1.2%. Operator error in DIA calculated for (Grove and Jerram, 2011), 10 operators, 14 thin sections, and measuring porosity área proposed an error of 1.2% of area. In our case, the total errors considered for point counting technique was 4.20% and 1.24% for the DIA technique.

2.2. Techniques

Optical transmitted light studies of thin sections applied to pore-network distribution require distinctions between mineral and pore networks according to their optical characteristics. The