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Characterizing pore fabric in sandstones with magnetic anisotropy methods: Initial results

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ABSTRACT

We describe and test a method to determine the directional properties of pore fabric in siliciclastic rocks using magnetic techniques. The approach is based on injecting into rock specimens a ferrofluid, a stable colloidal suspension of sub-domain magnetic particles in a liquid carrier, and measuring the magnetic susceptibility in different directions. Because the magnetic susceptibility after impregnation increases thirty times, the rock susceptibility can be neglected and therefore the anisotropy of magnetic ferrofluid susceptibility (AMFFS) provides an image of the 3D fabric and porosity in the rock. Our results on Triassic red sandstones suggest that both interparticle and intraparticle pores, which are measurable via AMFFS, are present and are largely determined by the micas and clays. Interparticle pores are most likely found between clay platelets, whereas intraparticle pores correspond to cleavage-plane pores within clay aggregates. Overall this study highlights that magnetic methods can be readily applied to siliciclastic rocks to characterize pore networks and more important, to determine the preferred orientation of the pores assemblage.

1. Introduction

The petrophysical characterization of geologic units that have the potential as reservoirs has become the focus of many studies during the past few years. Of particular importance are properties such as the 3D distribution of pore space and permeability in terrestrial, siliciclastic rocks such as sandstones and mudstones. Determining directional properties of pore networks in these reservoirs is indispensable to develop reservoir models and to better understanding the directional characteristics of fluid flow. In addition of being a key component for such models, porosity in clastic rocks is a fundamental property and is of paramount importance in many fields of Earth Sciences. Specifically, the direction of preferred orientation of pore long axes will exert a strong control on the direction of maximum permeability, and therefore the anisotropy of porosity is crucial for predicting fluid paths. When bedding is the sole primary layering in clastic rocks, it imparts the primary preferred plane for fluid flows, nevertheless, the details of how bedding and in particular preferred grain orientation that is responsible for such layering determine the anisotropy permeability in sedimentary rocks is still poorly known (e.g., Loucks et al., 2012). In this paper we use magnetic methods to the characterization of porosity anisotropy in red sandstones of Buntsandstein facies, which have great potential as reservoir. The Permo–Triassic sediments in Europe represent the hydrocarbon reservoirs with highest potential, and therefore understanding what factors determine their porosity is of paramount importance. Precise measurements of pore volume and structure in these rocks are necessary to model fluid storage and fluid flow modeling. Here we report the results of measuring the pore microstructure in Buntsandstein sandstones using magnetic approaches that allow a better understanding of the properties of anisotropy permeability.

Siliciclastic rocks display several porosity types (Pittman, 1979; Rouquerol et al., 1994; Dutton and Loucks, 2010). Loucks et al. (2010, 2012) grouped matrix-related porosity in three basic types, including interpores between grains and crystals, intrapores within minerals, and organic-matter pores. The voids size ranges from sub-capillary (=less than 0.002 mm) through super-capillary size (voids larger than 0.5 mm in diameter). Due to the large variety of industrial applications, a number of experimental techniques have been developed for determining porosity: gas adsorption, mercury and liquid intrusion, neutron and x-ray scattering, and thermoporometry, among other. Each method provides reliable information for different pore-size ranges, and the preference will depend on the expected range of pores size, sample properties, etc. The most commonly used techniques in rocks are mercury intrusion and liquid intrusion (e.g., Klaver et al., 2012). Nevertheless, porosity structure, and specifically the 3D fabric and hence permeability, has been barely studied, mostly due to instrumental availability. Pore properties such as shape and distribution are not completely revealed by thin section analysis

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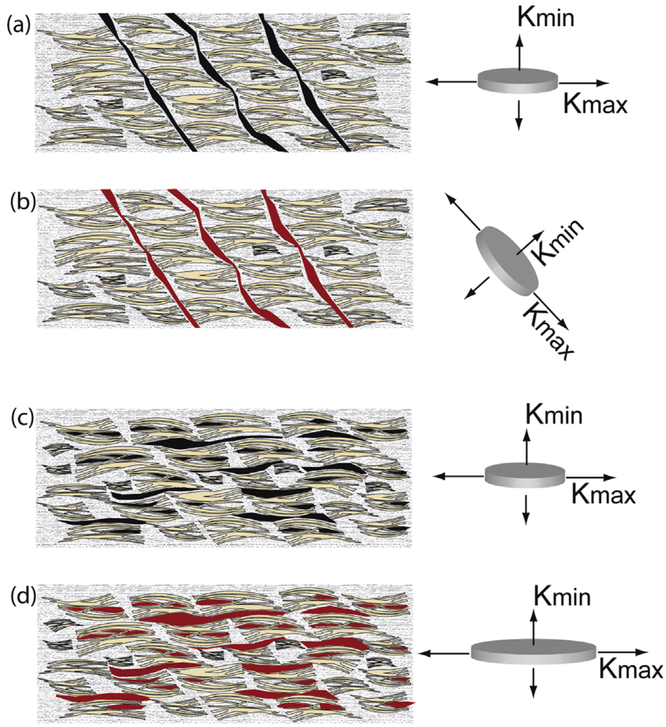

Fig. 1. Basis of the method. (a) In siliciclastic rocks having a primary, compaction-related fabric, clay minerals dominate the anisotropy of magnetic susceptibility (AMS). The presence of interparticle pores such as microcracks (depicted in black) will be unnoticed by the magnetic susceptibility, which will solely reveal a bedding-related fabric with the clay platelets oriented parallel to bedding (horizontal in the figure). The gray disk on the left depicts the orientation of the measured anisotropy of magnetic susceptibility, including the maximum and minimum axes (K_{max} and K_{min} respectively). (b) When pores are filled with a high magnetic susceptibility fluid (depicted in red), the magnetic fabric is then controlled by the pore orientation due to the large increase in susceptibility. The anisotropy of magnetic ferrofluid susceptibility (AMFFS) will then reflect the orientation of the filled-up microcracks. (c) Porosity (in black) is found between clay platelets and within clay aggregates (interparticle and intraparticle porosity). (d) Injection of a ferrofluid through the pores (depicted in red) will produce magnetic susceptibility and the AMFFS will then reflect the porosity and the AMFFS will reflect the porosity which is determined by the clay framework. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in 2D. X-ray computed tomography, on the other hand, is able of providing insights into a more complete view and connectedness of pores, but is limited by non uniqueness in the identification of minerals from their attenuation of x-rays, especially in the presence of very small pores less than about 1 µm (e.g., Roth et al., 2013). In order to measure the pore fabric and permeability anisotropy, we use an approach based on measuring the magnetic susceptibility of rock samples along different directions after impregnating the rocks with a ferrofluid suspension (Fig. 1). Due to the very high magnetic susceptibility of such ferrofluid, the measurement can be considered as a reading of the pore fabric network itself. Because samples are measured along different orientations (see "Methodology"), we determine the 3D pore fabric, including the orientation, shape and long axes of such voids referred to the geographic coordinates, as samples were oriented in the field. Such approach is based on previous attempts and applications (e.g., Hailwood et al., 1999), and the method is an extremely powerful technique to determine pore anisotropy in clastic rocks. The study of pore fabric with magnetic methods was originally outlined and tested by Pfleiderer and Halls (1990; 1994) and Pfleiderer and Kissel (1994), who used a water-based ferrofluid (EMG-705) to saturate the samples, and a less sensitive SI-2 magnetic susceptibility instrument (Sapphire Instruments) was used to determine the magnetic susceptibility. Hrouda et al. (2000) and Benson et al. (2003) improved the method by using an oil-based colloidal suspension ferrofluid (EMG-905), which ensures a higher penetration into the rocks. Recently, Robion et al. (2014) documented pore fabric using two different ferrofluids, water (EMG507) and oil (EMG909) based respectively, revealing the higher efficiency of the later and therefore it has been the choice for this study. We introduce some changes to the procedure by (1) using smaller sized samples to ensure full impregnation (4 cc as opposed to the previous studies which used 11 cc), (2) encapsulating the specimens in plastic boxes for better handling and to prevent contamination of the measuring coil by ferrofluid of the measuring coil, and (3) measuring the specimens with a more sensitive and rapid susceptibility bridge as explained below.

2. Material and methods

2.1. Anisotropy of magnetic susceptibility

The low field magnetic susceptibility of a rock (the ratio of magnetization M to the applied field H or $K=M/H$) is given by the total contribution of its bulk mineralogy, including paramagnetic (e.g., phyllosilicates, iron-bearing feldspars), diamagnetic (e.g., quartz, calcite) and ferromagnetic (sensu lato; e.g., magnetite, goethite, hematite) grains. An intrinsic property of all rock-forming minerals is that their magnetic susceptibility is anisotropic (Nye, 1957) and thus $K_{ij}=M_i/H_j$. The anisotropy of magnetic susceptibility (hereafter AMS) defines a symmetric, second-rank tensor that has six independent matrix elements. When the coordinate system is referred to the eigenvectors, these trace an ellipsoid that is known as the magnitude ellipsoid (Nye, 1957) whose semi-axes are the three principal susceptibilities ($K_{max} > K_{int} > K_{min}$). AMS in rocks depends mostly on the crystallographic preferred orientation of the individual components, compositional layering, distribution, and size of microfractures, and the shape fabric of grains (Fig. 1). Magnetic axes in clay minerals such as biotite conform to the density distributions of mineral lattice planes obtained by x-ray goniometry (Richter et al., 1993, Schmidt et al., 2009). Because densities from x-ray for chlorite and mica are perfectly reflected by the distribution of the minimum magnetic susceptibility axes, AMS can be used as a proxy for grain preferred orientation in a variety of rocks (e.g., Tarling and Hrouda, 1993). Some of the advantages of using AMS as opposed to x-ray, or other methods such as neutron diffraction is the rapidness of the measurement and the integration of thousands to grains as analysis are done on several cubic centimeters of rock at a time.

2.2. Samples and methodology

We sampled Triassic red silty sandstones pertaining to the classic Buntsandstein facies, which are overlying Paleozoic metasediments in the NW border of the Iberian Range (N Spain). Existing paleomagnetic and rockmagnetic data are due to Turner et al. (1989), Parés and Dinarès-Turell (1994), Rey et al. (1996), and Dinarès-Turell et al. (2005). The sedimentary rocks are medium grain sized (0.25–0.50 mm) and moderately sorted, defining sublitharenites. The Triassic beds are gently tilted by 20 degrees to the west but do not show any evidence for penetrative deformation. Four oriented hand samples were taken from different beds, in order to have a slight variability of grain size and composition, although overall the unit is rather homogeneous. Samples were mounted on plaster of Paris pedestals for drilling in the laboratory. A standard drill press equipped with a 18 mm- diameter drill bit was used to obtain several oriented 35 mm-long cores. A total of 42, 17-mm long specimens were obtained from the cores. The size of the specimens (height 17 mm, diameter 18 mm) allows using standard, non-magnetic, 7 cc plastic boxes with rounded edges, to