Integrated Study of Petrophysical Properties of Highly Heterogeneous Miocene Reefal Carbonate Rocks*

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Abstract

Post-depositional hydro-chemical alteration processes, including dissolution and precipitation, are controlling the development of multi-scale heterogeneities in carbonate rocks, leading to extremely variable and complex pore morphologies. As a result, the hydrodynamic properties may range over several orders of magnitude. For instance, more or less localized dissolution, cementation and dolomitization events can modify irreversibly the original structure, with the formation of highly conductive zones or, at the opposite, permeability barriers. Because of the growing heterogeneity and feedback effects of the flow, transport and reaction, virtually all types of porosity can be found within the same reservoir, depending on the hydrochemical forcing. The characterization of the pore arrangements and their relations with the macroscopic properties is essential to parameterize reservoir exploitation or groundwater contamination models (Choquette and Pray, 1970; Chilingarian et al., 1992; Lucia, 1995; Moore, 2001; Mylroie and Carew, 2003).

Introduction

In reservoir engineering, hydrodynamic properties can be estimated from electrical resistivity data using heuristic models (e.g. Archie and Kozeny-Carman's laws) relating electrical conductivity to porosity and permeability. The electrical resistivity is actually one of the most commonly used properties to describe porous media morphology. Indeed the electric current being predominantly conducted by the fluid phase through the connected fraction of the pore space, electrical resistivity measurements lead to precious information about the pore network structure. Electrical resistivity has been widely used to study the lithology, the porosity and the water saturation of reservoirs since the pioneering works of Schlumberger (1972, 1974). However, although the relationship between resistivity and porosity, often achieved by using the empirical Archie's law (Archie, 1942), has been proven to be predictive for many sandstone reservoir, it often faces strong limitations when applied to carbonate rocks that usually display complex pore structures (Verwer et al., 2011). The Archie's exponent, also called the cementation factor, quantifies the variation of the electrical resistivity for a given porosity. It is often set to 2 in carbonate rocks. However, it can be extremely variable, depending on the shape and type of grains and pores, the specific surface area or the tortuosity for example (Salem and Chilingarian, 1999). In addition to the cementation factor, the electrical tortuosity is also used to link resistivity to porosity by the mean of empirical laws (Archie, 1942; Wyllie and Rose, 1950; Winsauer et al., 1952; Cornell and Katz, 1953; Clenell, 1997). Then the permeability is usually predict from the combination of the porosity, the critical pore size, the specific surface, the electrical resistivity and/or the electrical tortuosity (Kozeny (1927), Carman (1937, 1956), Bear (1972) and Dullien (1979). The many existing empirical relationships are usually derived from simple models of the pore space and often face limitations when applied to a real media, leading to false permeability estimates.

Discussion

The present study is investigating the link between porosity, electrical resistivity and permeability by examining their relations with parameters that characterize the three-dimensional (3D) geometry of the pore network. The overall aim is twofold: first propose a pertinent methodology for investigating highly heterogeneous reservoir from pore scale to the scale at which effective macroscopic properties and parameters are usually measured, and second bring new data on carbonate rocks that have experienced many hydrochemical alteration events, emphasizing on the control of pore structure on the petrophysical and transport properties in both case.

This study focuses on the petrophysical properties of a Miocene reefal platform from Mallorca, Spain, first described by Esteban (1979) and Pomar et al. (1996). The experimental site of Ses Sitjoles, located 6 km from the coast, comprises cored boreholes of 100 m depth which sample the three units of the Miocene reef complex: intern platform-like structures at the top, karstified reefal constructions in the middle and forereef deposits at the base. The actually observed rocks have been submitted to various hydrological environments and chemical processes linked to saline intrusions. Repeated cycles characterized by secondary dissolution porosity, cementation features and mineral replacement or stabilization are extensively observed, producing an increase of the pore size variability. A particular attention was drawn to three zones showing drastic change in porosity happening over a few cm only, mostly located at the limit between two different geological units (25 m depth, 37 m depth and 61 m depth). A set of petrophysical measurements and calculations (porosity, density, electrical resistivity, formation factor, cementation factor and tortuosity) were conducted on 46 mini cores of 9 mm-diameter and 18 mm-length sampled in the three zones. One of the zones (25 m depth) was fully described with permeability measurements, mercury intrusion porosimetry and the characterization of the 3D pore structure X-Ray microtomography (XRMT) images, obtained at the European Synchrotron Radiation Facility (ESRF) in Grenoble with a pixel size of 5.06 μm. The data processing included the determination of the connected porosity, percolation clusters, mobile/immobile domain and the computation of the electrical tortuosity and microstructural descriptors such as the pore-size and chord length distribution functions and the specific surface.

Results

The Archie’s relationship between porosity and electrical resistivity describes quite efficiently the data sets with a cementation factor ranging from 2 to 2.6 depending on the zone and tortuosity values ranging from 4.8 to 9.8. However, the tightest samples significantly deviate from the linear relationship followed by most samples with porosity above 10% and each zone present samples with similar porosity but different values of formation factor, which confirms that the porosity alone is not sufficient to explain electrical behavior in carbonates and that the porous media should be further investigated to avoid false porosity and thus permeability estimates.

The detailed analysis of the pore structure of the zone at 25 m depth suggests that samples with large simple pores (high pore-size and low specific surface), such as vugs or molds, have high values of resistivity, cementation factor and electrical tortuosity, and that inversely, samples characterized by a complex network with small pores (small pore-size and high specific surface) have low values of resistivity, cementation factor and electrical tortuosity. The results also show that, contrary to what is usually assumed, the most porous and less resistive and tortuous sample (sample N) is not the most permeable, and that a much less porous and more resistive and tortuous sample (sample A) can be more permeable (Figure 1). The major difference between the two samples is the size of the pore-diameter connecting the pore network. In this particular data set, hydrodynamic flow appears to depend on the critical pore size of the percolating network, rather than on electrical formation factor or tortuosity, which are also often used as a measure of flow efficiency in many Kozeny-Carman type of equations.

Conclusion

The overall study highlights the remarkable μm-scale heterogeneity of the studied carbonate data set and the strong control that this heterogeneity has on the macroscopic measured petrophysical and hydrodynamical properties. In reservoir engineering, porosity, water saturation and permeability are usually estimated from downhole electrical data using heuristic resistivity-porosity and porosity-permeability relationships that have been proven successful in sandstones. However, it is shown here that we cannot rely on these relationships in carbonate rocks, precisely because of the combination of two realities: first, heterogeneities occur at scales smaller that than of the integration volume of the borehole geophysical methods (tens to hundreds of cubic centimeters in the best cases) and second, these μm to cm-scale heterogeneities strongly influence the measured macroscopic physical parameters that are then used to evaluate the hydrodynamic properties of the rock. For application to such highly heterogeneous carbonates, we believe that borehole geophysical measurements must be associated with both multi-scale 3D imagery techniques and core-scale geophysical properties measurements in order to describe the scale dependencies of the parameter relationships and obtain pertinent macroscale upscaled rules in fine.

References

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Journal of Petroleum Technology, v. 5, p. 1-8.

Bear, J., 1972, Dynamics of fluids in porous media: New York, American Elsevier, 166p.

Carman, P.C., 1956, Flow of gases through porous media: London, Butterworths, 182p.

Chilingarian, G.V., S.J. Mazzullo, and H.H. Rieke, 1992, Carbonate Reservoir Characterization: A Geologic-Engineering Analysis, Part I (Developments in Petroleum Science): Amsterdam, Elsevier Science, 640 p.

Choquette, P.W., and L.C. Pray, 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates: AAPG Bulletin, v. 54, p. 207-244.

Cornell, D., and D.L. Katz, 1953, Flow of gases through consolidated porous media: Industrial and Engineering Chemistry: v. 45, p. 2145-2152.

Dullien, F.A.L., 1979, Porous media: fluid transport and pore structure: New-York, Academic Press, 396p.

Esteban, M., 1979, Significance of the upper Miocene reefs in the Western Mediterranean: Paleography, Palaeoclimatology, Palaeoecology, v. 29, p. 169-188.

Kozeny, J., 1927, Über Kapillare Leitung des Wassers im Boden: Sitzungsberichte der Akademie der Wissenschaften in Wein, v. 136, p. 127-306.

Lucia, F.J., 1995, Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization: AAPG Bulletin, v. 79, p. 1275-1300.

Moore, C.H., 2001, Carbonate reservoirs, porosity evolution and diagenesis in a sequence stratigraphic framework, developments in sedimentology: Oxford, Elsevier, 444 p.

Mylroie, J.E. and J.L. Carew, 2003, Karst development on carbonate islands: Speleogenesis and Evolution of Karst Aquifers, v.1, no. 1, 21 p.

Pomar, L., W.C. Ward, and D.G. Green, 1996, Upper Miocene reef complex of the Llucmajor area, Mallorca, Spain: SEPM Concepts in Sedimentology and Paleontology, v. 5, p. 191-225.

Salem, H.S., and G.V. Chilingarian, 1999, The cementation factor for Archie's equation for shaly sandstone reservoirs: Journal of Petroleum Science and Engineering, v. 23, p. 83-93.

Schlumberger, 1972, Log interpretation, Vol. I: Principles: New York, Schlumberger Limited, 113 p.

Schlumberger, 1974, Log interpretation, Vol. II: Applications: New York, Schlumberger Limited, 116 p.

Verwer, K., G.P. Eberli, and R.J. Weger, 2011, Effects of pore structure on electrical resistivity in carbonates: AAPG Bulletin, v. 95/2, p. 175-190.

Winsauer, W.O., H.M. Shearing, P.H. Masson, and M. Williams, 1952. Resistivity of brine saturated sands in relation to pore geometry: AAPG Bulletin, v. 36, p. 253-277.

Wyllie, M.R.J., and W.D. Rose, 1950, Some theoretical considerations related to quantitative evaluation of the physical evaluation of the physical characteristics of reservoir rocks from electric log data: Journal of Petroleum Technology, v. 2, p. 105-118.

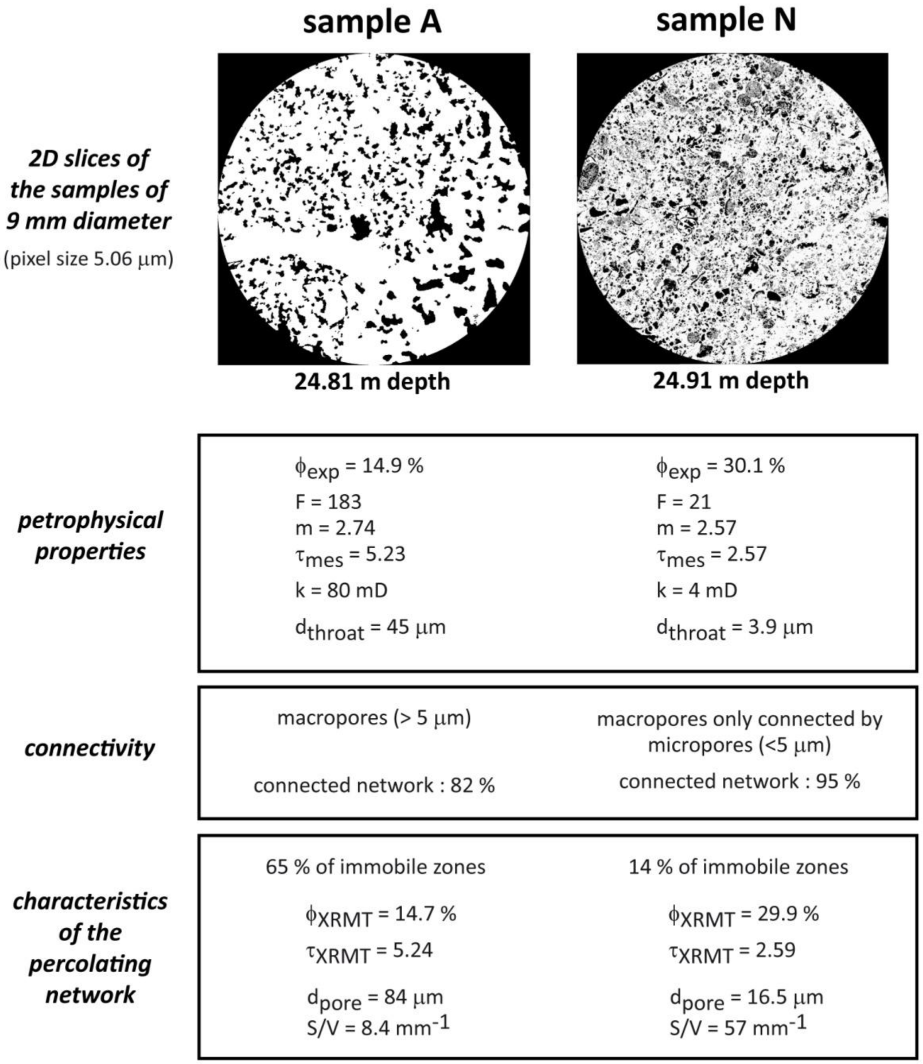

Figure 1. Results of petrophysical measurements and XRMT data in the case of two different samples (sample A and sample N). The images are examples of a 2D cross-section of the samples. ϕ_{exp} is the porosity measured with the triple weighting method, F, m and τ_{mes} are respectively the formation factor, the Archie's exponent and the electrical tortuosity calculated from electrical resistivity measurements, k is the permeability and d_{throat} is the mean pore entry (throat) diameter given by mercury intrusion porosimetry tests. ϕ_{XRMT} and τ_{XRMT} are respectively the connected porosity and the electrical tortuosity calculated on the XRMT images, and d_{pore} and S/V are respectively the mean diameter of the pores and the specific surface, both also computed on the images.