Tectonophysics 503 (2011) 18–33

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

An integrated study of the petrophysical properties of carbonate rocks from the "Oolithe Blanche" formation in the Paris Basin

Lisa Casteleyn [a,*], Philippe Robion [a], Christian David [a], Pierre-Yves Collin [b,c], Beatriz Menéndez [a], Nathalie Fernandes [d], Guy Desaubliaux [d], Christophe Rigollet [e]

[a] Université de Cergy-Pontoise, Laboratoire Géosciences et Environnement Cergy, 5 Mail Gay-Lussac, F-95031 Cergy-Pontoise cedex, France
[b] UPMC Univ. Paris 06, UMR 7193, ISTeP, Case 117, 4 Place Jussieu, F-75252, Paris cedex 05, France
[c] CNRS, UMR 7193, ISTeP, Case 117, 4 Place Jussieu, F-75252, Paris cedex 05, France
[d] GdFSuez, 361 av. Président Wilson, 93211 Saint-Denis La Plaine, France
[e] BRGM, 3 Avenue C. Guillemin, BP 36009, 45060 Orléans cedex 2, France

ARTICLE INFO

Article history:
Received 30 April 2010
Received in revised form 23 July 2010
Accepted 21 September 2010
Available online 29 September 2010

Keywords:
Permeability
Seismic velocity
Electrical conductivity
Microstructure
Oolite
Carbonate rocks

ABSTRACT

Petrophysical properties were measured on oolitic limestone from the Oolithe Blanche formation (middle Jurassic) in the Paris Basin. Eighteen oriented blocks were collected from three outcrops regarding of the three main facies, oolitic shoal facies, tide dominated facies and prograding oolitic facies. We investigated the relationship between both compressional wave and electrical conductivity with different petrophysical properties such as porosity (water porosity and mercury porosity), permeability and capillarity imbibition. These have led us to relate the variations of petrophysical properties to several microstructural parameters, among them the microporous structure is the most important. Concerning P wave velocities, the general trend observed is as expected a decrease of velocities as the porosity increases but with a significant fluctuation of velocities for a given value of porosity. We have used two distinct effective medium approximations to describe the velocity variations: the self-consistent (SC) approximation and the cemented contact theory (CCT) but no unique model can simply explain our velocity behaviours. The main parameter that controls the P wave velocities is the distribution of microporosity inside oolites: for samples with velocities higher than 4 km/s the microporosity is mainly located in the rim of the ooids while for samples with velocity lower than 4 km/s the microporosity is homogeneous across the ooids. Acoustical fabrics, which are controlled by the facies, indicate that sedimentary textural components such as the amount of cement and arrangement of elements within the oolitic limestones (bioclasts, pellets and ooids) and their degree of connectivity may have some influences on the acoustic velocities.

In contrast with acoustic properties, the electrical conductivity data are not so clustered by facies indicating that transport properties are more influenced by microstructural heterogeneities. One single Archie's law can well account for all the data sets but these sets also show a large range of tortuosity factor related to the microporosity arrangement inside oolites.

Some good predictive permeability modeling were found using mercury injection spectra. Our investigations reveal that, the best way for fluids to flow is to pass through the microporosity in the oolites, and that permeability depends mainly of the connectivity of the ooids, which is certainly related to the facies.

1. Introduction

The fluid flow properties in carbonate rocks are mainly controlled by both the pore space and the sedimentological fabric which have both been used for a long time as key parameters for the interpretation of carbonate reservoir properties (Archie, 1942; Choquette and Pray, 1970; Lucia, 1995). Recent work provided by Lønøy (2006), refines this approach by proposing to incorporate pore size and pore shape distributions that reflect more accurately the depositional fabric and the latter diagenetic history more or less intricate (Enos and Sawatsky, 1981; Heasley et al., 2000; Ehrenberg et al., 2006a,b). Therefore, investigating the pore size distribution is a challenging issue in the evaluation of reservoir rock properties and particularly in the prediction of permeability. An indirect way to get insight into the pore size distribution is through acoustic and electrical measurements which are both related to pore network properties. Although these approaches are indirect in order to estimate permeability, they are less time consuming and can be used both in *in situ* conditions and in laboratory. In order to get the correct rock properties under in situ conditions, both stresses and temperature need to be reproduced in laboratory experiments.

* Corresponding author. Tel.: +33 134257367.
E-mail address: lisa.casteleyn@u-cergy.fr (L. Casteleyn).

0040-1951/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2010.09.031

Many studies have focused on the relationships between porosity and acoustic velocity (e.g. Verwer et al., 2008 and references therein). Rafavich et al. (1984) showed that porosity is the first factor with density and in first approximation the time average velocity can be used to estimate porosity. Anselmetti and Eberli (1993, 1997, 1999) show on various carbonate lithologies that sonic velocities are stronger in rocks containing moldic and intraparticle porosity than in rocks containing interparticle porosity. Other studies (Baechle et al., 2008), with a more quantitative approach using effective medium concepts, have shown how a dual porosity (micro vs. macroporosity) can scatter the velocities with a factor up to 2. In a recent work, Weger et al. (2009) by using digital image analysis, proposed that the most relevant parameters that affect acoustic velocity are pore size and specific surface area. As a rule, carbonates with high specific surface and small pore size distribution have a low velocity while carbonate with simple pore structure and large pores show high acoustic velocity. Few works have been dealing with relationships between pore structure and resistivity measurement combining microscopic observations and laboratory measurements on carbonate rocks.

The aim of this paper is to characterize the influence of pore structures on acoustic velocity, electrical conductivity and permeability in three distinct facies sampled in the "Oolithe Blanche" formation from the Paris Basin. In a previous study (Casteleyn et al., 2010) we demonstrated a close relationship between the fluid flow properties (permeability and capillary imbibition) and the nature of sedimentary facies as well as the organization of the porosity. The three parameters that control these properties are the size of the porosity i.e. micro-, meso- and macroporosity, the quantity and nature of the matrix (sparite or micrite), and the heterogeneity of microporosity within ooid grains (presence of a rim porosity). Depending on the combination of these different parameters, permeability can vary over two orders of magnitude, from 10^{-1} millidarcy up to 10 millidarcy between different sedimentary facies within the same formation. Our goal is to present additional petrophysical data on the "Oolithe Blanche" formation, focusing on acoustic and electrical properties. We will show that this new data set complements the previous one (Casteleyn et al., 2010) and provides additional insight into the complexity of our carbonate rocks. The link between the properties investigated here and fluid flow as well as microstructural properties will be discussed, in particular using different models for the prediction of the rock permeability from microstructural attributes.

2. Geologic settings, sampling and previous results

The "Oolithe Blanche" formation is present in the Paris Basin at more than 1000 m depth in the middle of the basin and on outcrops at the basin edges. This Bathonian formation is about 70–80 m thick and is composed of very shallow marine oolitic and bioclastic limestones. Three main sedimentological facies were defined depending on the depositional environments (Fig. 1). 1) The oolitic shoal facies is characterized by a high energy shoal oolitic deposit (Fig. 2a), 2) the tide dominated facies is characterized by the influence of tidal processes on the deposit (Fig. 2b) and 3) the prograding oolitic facies is characterized by an accumulation of oolitic lobes (Fig. 2c). Each facies is composed of three main elements: oolites, pellets and bioclasts. Oolites (Fig. 2d) and pellets are made of micrite which is a porous arrangement of calcite microcrystals (<4 μm). The difference between oolites and pellets is that oolites are made up of circular laminae and pellets have no internal structure. Bioclasts (echinoderms, lamellibranchia, brachiopods, gastropods, foraminifers) are lumped in a single category and they are mainly composed by non porous calcite phenocrystals (>10 μm) (Fig. 2e and f). Two cement type are observed. Either a micritic matrix or a sparite cement. Micrite and sparite are both made of calcite crystals. Mains differences between them are crystal size and connections between crystals. Micrite is an arrangement of calcite microcrystal (<4 μm, Fig. 2g) and sparite is composed of phenocrystals (>4 μm). In case of micrite, the arrangement of crystals is discontinuous and allows a fluid flow whereas sparite arrangement is continuous and non porous. From sedimentological point of view, micrite corresponds to crystallization of the early carbonate mud while sparite corresponds to some latter precipitation processes.

Effects of different depositional environment on samples are observed on microstructural arrangements between the mains elements within the cement. These observations are synthesized on pore network models developed in Casteleyn et al. (2010) and which will be presented at the end of the paragraph.

Oriented block samples of about 30 cm edges were collected on outcrops in each of the facies identified in the formation. In order to identify possible horizontal variations in facies distribution three quarries were investigated at the scale of the whole formation. The base of the formation is present in the Bierry-Les-Belles-Fontaines quarry and the top in the Ravières and Massangis quarries. 18 oriented blocks were collected in the three facies: 5 in the tide dominated facies (BY08, BY09, RAV02, RAV03 and RAV05), 3 in the oolitic shoal facies (BY04, BY05 and RAV01) and 10 in the prograding oolitic facies (BY01, BY02, BY03, BY10, BY11, MA01, MA02, MA03, MA04 and RAV03). The number of blocks sampled on each facies is dependent on the apparent homogeneity or heterogeneity of each facies.

On these samples Casteleyn et al. (2010) measured several petrophysical properties: porosity (using the water saturation triple weight method), pore size distribution derived from mercury injection tests, water permeability and capillary imbibition

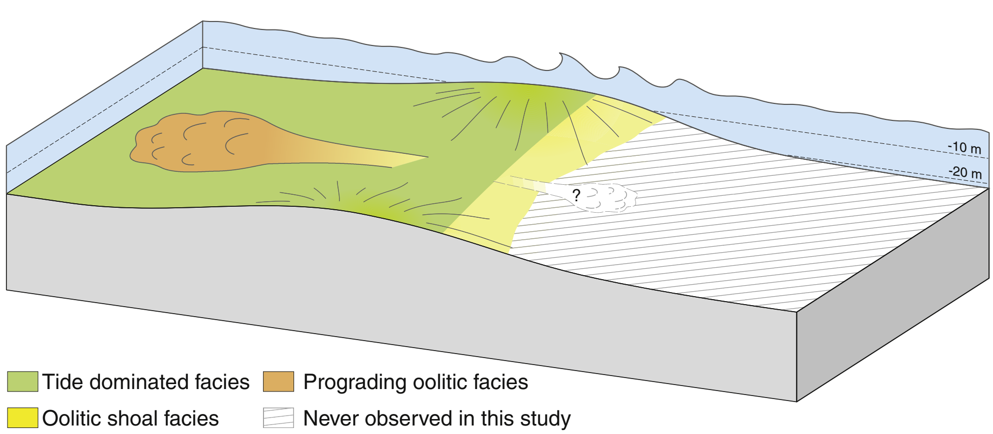

Fig. 1. Block diagram with the distribution of the three main facies. From Casteleyn et al., 2010.