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# Influence of microporosity distribution on the mechanical behavior of oolithic carbonate rocks

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## HIGHLIGHTS

- Oolithic carbonate rocks from the Paris Basin are studied under in situ conditions.
- Elastic and mechanical properties are controlled by porosity distribution in micrite.
- Permeability and cap models explain the contrasting behavior with pore distribution.

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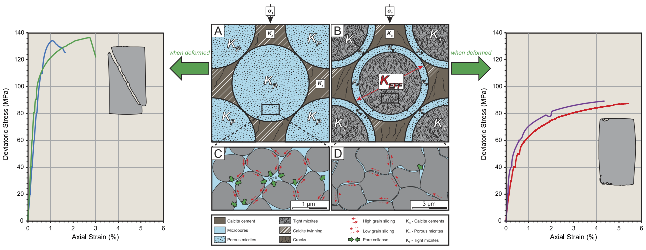
## GRAPHICAL ABSTRACT



## ABSTRACT

The mechanical behavior of oolithic carbonate rocks was investigated for selected rocks with two different microstructural attributes: uniform (UP) and rimmed (RP) distribution of microporosity within ooids. These oolithic carbonate rocks are from the Oolithe Blanche formation, a deep saline aquifer in the Paris Basin, and a possible target for $CO_2$ sequestration and geothermal production. Samples of similar physical properties (porosity, grain diameter, cement content) but different microporosity textures were deformed under triaxial configuration, in water saturated conditions, at 28 MPa of confining pressure, 5 MPa of pore pressure and at a temperature of 55 °C. During the experiments, acoustic velocities were monitored, and permeability was measured. The results show that the mechanical behavior of these microporous carbonates are strongly controlled by the microporosity distribution within the grains, at the origin of variations in elastic properties, mechanical strength and failure mode. The lower velocities measured in UP samples indicate a larger compliance of the whole structure. The mechanical response indicates that UP samples are characterized by a ductile behavior whereas RP samples display a brittle behavior. Using a conceptual model for the failure envelope of both rocks, our observations can be accounted for if one considers a significant variation of the critical pressure $P^*$, with UP samples having a lower $P^*$ than RP samples. The permeability evolution under stress was

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interpreted using a revised Kozeny–Carman equation, showing that fluid flow is strongly affected by the tortuosity of the pore space, which is controlled by the microporosity distribution within the ooids. This study brings new insight into the parameters controlling the physical and mechanical response of oolithic carbonates, and the possible impact on production of geothermal energy at depth or storativity for $CO_2$ sequestration operations.

## 1. Introduction

Deformation in porous rocks is a crucial problem in fault development and reservoir management. Active tectonics and extraction of fluids modify the pore pressure in a reservoir, causing variations of the effective stress and possibly leading to faulting and inelastic deformation. The ability to interpret and predict the occurrence and extent of such deformation depends on a fundamental understanding of the mechanical properties (inelastic behavior, failure mode) of porous rocks.

The Oolithe Blanche formation, is one of the two major deep saline aquifers in the Paris Basin (France). This formation has been used for over thirty years in the exploitation of geothermal energy and new wells are still implemented nowadays. This reservoir was also selected by the French geological survey (BRGM) as a potential target for $CO_2$ geological storage.[1] However, several studies concerning both type of exploitations showed that the Oolithe Blanche forms a complex carbonate reservoir presenting heterogeneous petrophysical and microstructural properties.[2–6]

Many studies using P-wave velocities measurements have shown that dynamic moduli of carbonate rocks are controlled by several microstructural parameters such as rock fabric, pore type and shape, porosity and pore fluid, making it difficult to attribute changes in seismic expression to any one parameter.[3,4,6–15] Elastic waves are, in essence, small mechanical perturbations and are therefore affected by the rock microstructure and rock deformation processes. An effect is thus logically expected on the static moduli, which are directly measured during deformation, and therefore on the overall mechanical response of carbonate rocks. Numerous studies have described mechanical compaction in carbonate rocks.[16–20] The brittle to ductile transition in carbonates shows different attributes than those found in silicate rocks. Limestones undergo the brittle to ductile transition at room temperature for confining pressures accessible in the laboratory[21–24] because calcite requires relatively low shear stresses to initiate mechanical twinning and dislocation. In limestones of intermediate porosity (from 3% to 18%), dilatancy and shear localization is developed under low confining pressure, while strain hardening and shear-enhanced compaction are observed at high confining pressure.[16–18] However at high confining pressure and after a certain amount of strain-hardening, the samples consistently evolve from compaction to dilatancy. This characteristic of dilatant and compactant failure in carbonates is a common feature shared with many types of porous sandstones.[25]

Motivated by the microstructural observations, a number of micromechanical models have been proposed to capture the brittle and ductile failure in porous rock. In the brittle field, models involving pore-emanated crack[26] and sliding wing crack[27–29] have been tested to interpret the experimental data. In relation to these models, analytic estimates of the brittle strength as a function of the initial damage have been derived[20,30,31] and the theoretical predictions can conveniently be compared with laboratory data. In the ductile field, the grain crushing[30,32] and Hertzian fracture[25,33] models have been developed for analyses of pore collapse in carbonate and siliciclastic rocks, respectively. However, considering the extreme heterogeneity of pore systems and microstructures in carbonate rocks, the pore collapse model for limestone[30] would likely be inappropriate in situations where dual porosity is not present, like in carbonates dominated by micritic structures only. To date, there is a lack of microstructural data and observations to constrain more elaborate models.

A key question on the mechanics of inelastic deformation is: how does the starting microstructure of porous carbonates trigger or inhibit the development of inelastic compaction at a given pressure? In this paper, we address this major issue by presenting new physical and mechanical data on porous carbonates with different microstructural settings. We also provide insights on the dominant micromechanism of deformation that leads to macroscopic compaction in porous carbonates. Finally, we investigate the change in ultrasonic velocities and permeability as a function of increasing hydrostatic pressure and deviatoric stress.

## 2. Sampling and experimental set-up

### 2.1. Sample selection and preparation

The Oolithe Blanche samples are from the same blocks studied by Casteleyn et al.[3,4] and Makhloufi et al.,[6] who have provided a fully detailed petrophysical description. The blocks come from three quarries located in the Paris Basin (France), in the north of Burgundy near the towns of Massangis (N 47°37′19.22″; E 3°57′22.49″), Bierry-Les-Belles-Fontaines (N 47°36′42.96″; E 4°10′48.78″) and Ravières (N 47°43′34.92″; E 4°14′21.36″) (Fig. 1). The Oolithe Blanche formation is an ooid-rich limestone with minor bioclastic content (echinoderms, bivalves, brachiopods, gastropods, bryozoans and foraminiferas). Ooids found in this limestone show laminations typical of marine ooids formed in a disturbed environment. Macroporosity is not observed and the dominant inter-crystalline microporosity (pore diameter $< 10\ \mu m$ as defined by Lønøy[34]) occurs in a lithified matrix located in the grains and is