# Challenges and Current Advances in the Rock Physics of Carbonate Rocks*

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## Abstract

Carbonate rocks show no one-to-one relationship between porosity and permeability, nor between porosity and velocity. On the one hand, permeability depends on the ability to conduct fluid flow, which is controlled by both the size of the pores and the tortuosity of the interconnected pore space. On the other hand, velocities depend on pore compliance and stiffness at the grain contacts, which are controlled respectively by pore shape and the amount of intergranular cement. Diagenesis during burial, cement dissolution and compaction under stress, all contribute to the evolution of the rock connectivity and stiffness over time. Although this is applicable to all porous rocks, carbonate rocks are especially susceptible to these phenomena because of their proneness to react chemically. In the long-term, this contributes to their heterogeneous texture and fabric, thus greatly increasing the chance for variability and complicating how transport and elastic properties relate to the diagenetic trends of these rocks. In the short-term, complex rock-fluid interactions violate most of the assumptions of purely mechanical models used for predictive property modeling, thus challenging any attempt of quantitative, geophysical monitoring.

We show in this presentation the results of several laboratory investigations and high-resolution imaging (SEM and CT-scan) aiming at understanding the fundamental physics and chemistry responsible for the interplay between flow, chemical reactions, microstructure, and deformation in carbonates. Understanding this phenomenological interplay is important to model the parameters controlling transport and elastic properties in carbonates.

**Laboratory Observations and Modeling Input**

The first avenue of research addresses the question of how to interpret seismically detected changes in a carbonate/fluid system and how to build well-adapted predictive models. The small expected seismic signature (i.e., relatively modest seismic amplitude change) upon water flood and the often-questioned applicability of the Gassmann's fluid substitution model are both detrimental factors while assessing the feasibility of time-lapse seismic. Time-lapse laboratory experiments measuring the variation of acoustic properties upon injection of $CO_2$ show that both P-wave and S-wave velocity of the carbonate dry frame changes upon injection (Figure 1a and Figure b). Time-lapse imaging show that changes are due to injection-induced dissolution leading to compaction under stress which mainly affect the highest-surface area components of carbonates (i.e., cement at the grain contacts and micrite phase) (Figure 3a and Figure 3b). The weakening of the rock frame upon injection also leads to an increased sensitivity of velocity to pressure implying a larger compliance of the rock frame, and in turn, a larger sensitivity of velocity to the presence of fluids. This wealth of observations makes it clear that modeling changes in a carbonate/fluid system cannot be treated as a pure fluid-substitution problem. Both chemical and physical mechanisms are responsible for the observed changes and they cannot be de-coupled: porosity, rock strength, elastic moduli of the carbonate frame must be also considered time-variant parameters while assessing the 4D seismic signature.

A second avenue of research is addressing the question whether the seismic and transport response resulting from chemo-mechanical processes upon injection is facies-dependent. *Can trends of how porosity, permeability, compressional and shear velocities vary upon injection be established?* Figure 2a shows the evolution of P-wave and S-wave velocity (top left and right, respectively) and permeability (bottom, center) of the injected samples as functions of porosity. Though the number of injected pore volumes is the same for each sample, trends are similar for samples belonging to the same formation. In chalky, micritic carbonates, both porosity and permeability linearly increase upon injection, while velocities decrease. In tight limestones, porosity and velocity show negligible change upon injection, while permeability suddenly increases after reaching a critical threshold. All data are normalized with respect to the initial value and refer to properties of the carbonate frame after injection; thus they reflect how the modifications in the pore attributes and microstructure affect velocity and permeability.

In Figure 2b data are compared to the natural diagenetic trends of untreated carbonate samples (gray symbols). Surprisingly, the evolution of velocity and permeability of the injected samples follows that expressed by the natural diagenetic trends. These results imply that pore attributes and microstructure are modified in a way that is characteristic of each carbonate facies. We show how these results help narrow the choice of input parameters when modeling the evolution of the porosity-permeability/velocity trends in carbonates.

## Conclusions

So far, laboratory experiments showed that fluid-solid chemical reactions inducing mechanical deformations in carbonates are highly nonlinear, strongly coupled, and controlled by size and geometry of porosity as well as spatial distribution and surface area of the solid phases composing carbonate rocks. That is intimately connected to the rock depositional environment and facies. Because of the complexity of carbonates and the need to understand the link (and its changes) between seismic and transport response and rock microstructure so that coupled reactive fluid flow-mechanical deformation models can be developed at the pore-scale, we are also conducting laboratory experiments and time-lapse imaging on synthetic samples mimicking composition, microstructure, and pore structure (i.e., pore shape and size) of carbonates (Figure 4a and Figure 4b). Trends of the measured rock properties and their evolution upon injection on controlled microstructures may provide physical and well-controlled bounds which help in understanding how to model the processes controlling the rock physics of carbonates and their geophysical response to deformation upon rock-fluid interaction.
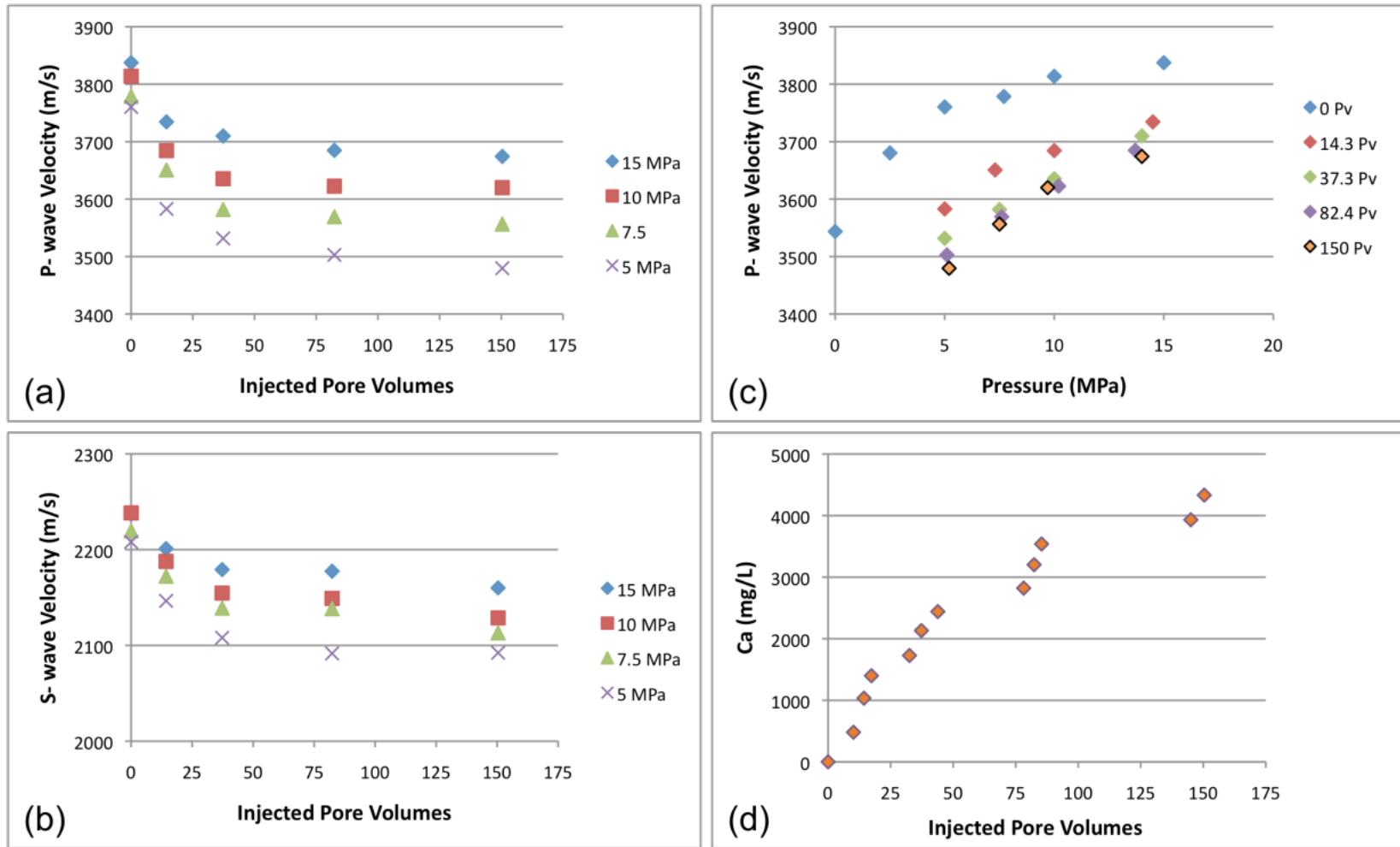
Figure 1. Variation of P-wave (a) and S-wave (b) velocity of the carbonate frame as functions of injected pore volumes. Data are color coded as a function of confining pressure, which seems to affect the magnitude of changes. Injected pore fluid pressure was set at 12 MPa. (c) Variation of the sensitivity of P-wave velocity to confining pressure upon proceeding with injection. (d) Variation of the amount Ca cations (cumulative) within the output fluid collected after each injection which testify the occurrence of dissolution.
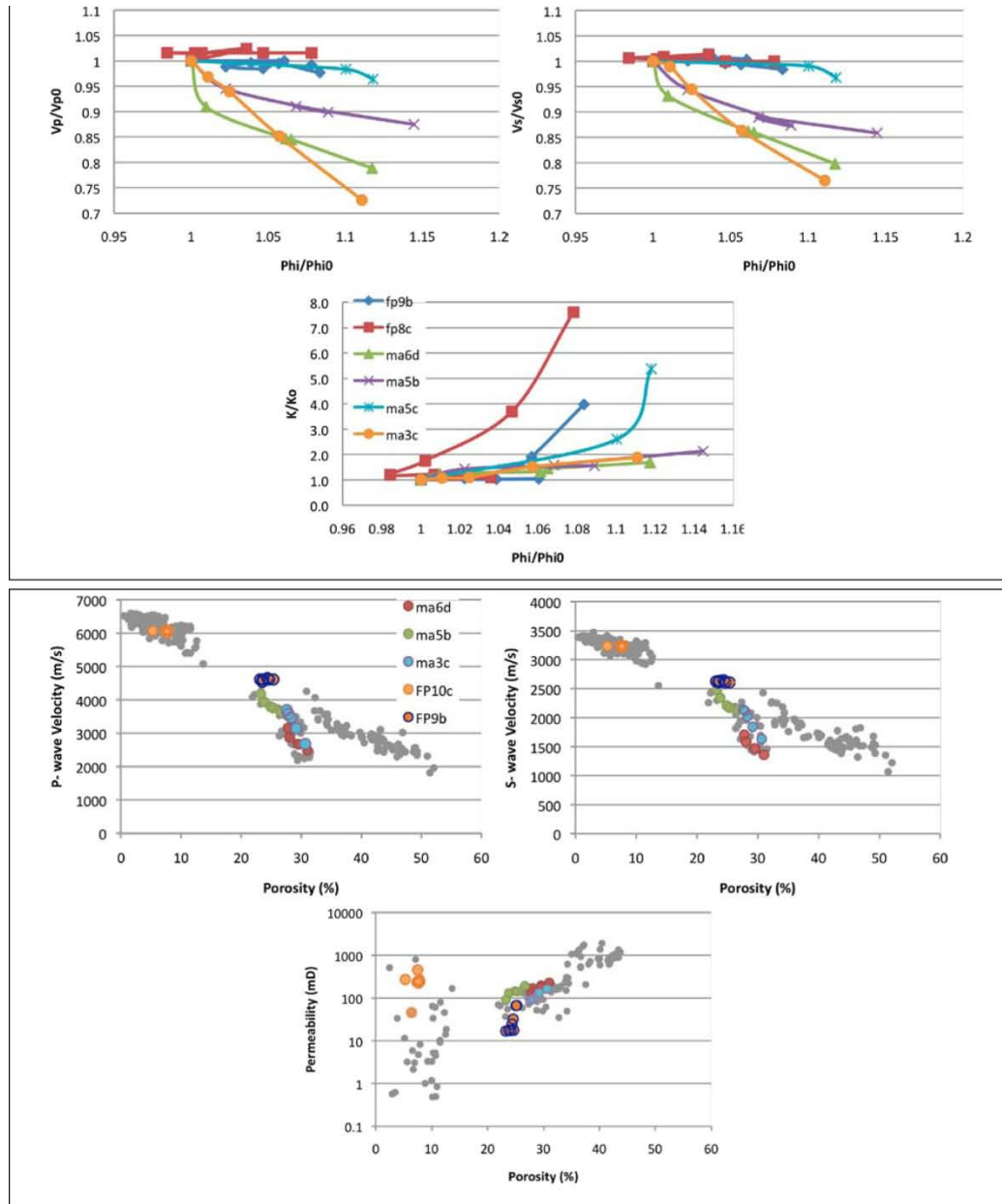
Figure 2. (a) Top panel: Evolution of P-wave and S-wave velocity and permeability of the injected samples as functions of porosity. All parameters are normalized with the respect to their pre-injection values. Data refer to dry samples measured after injection. (b) Bottom panel: Evolution of P-wave and S-wave velocity and permeability of the injected samples as functions of porosity. Data are compared to the natural diagenetic trends of untreated carbonate samples (gray symbols). Data refer to dry samples measured after each injection.
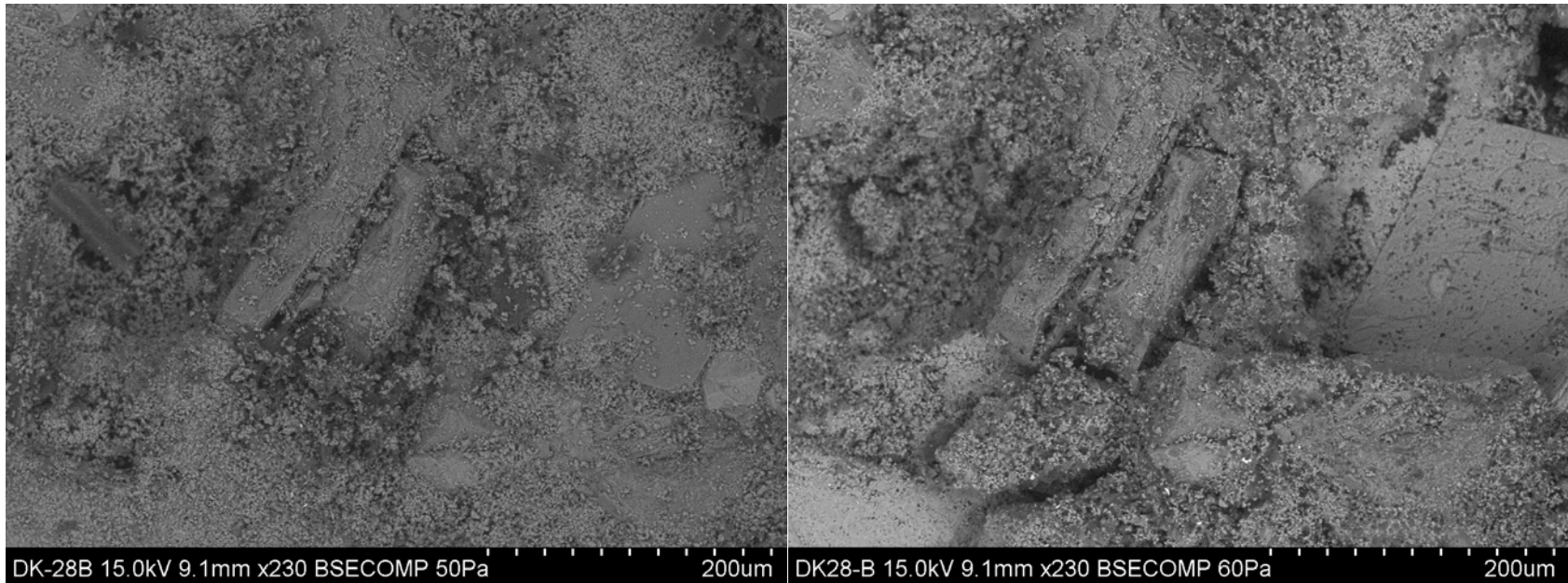
Figure 3. Time-Lapse SEM images monitoring the permanent changes induced in the rock microstructure upon $CO_2$ injection. The picture on the left shows the rock microstructure before injection while the one on the right shows how it has changed after the $CO_2$ injection. Flooding mainly affects the highest-surface area components of carbonates (i.e., cement at the grain contacts and the micrite phase) which then leads P-wave and S-wave velocities to decrease.
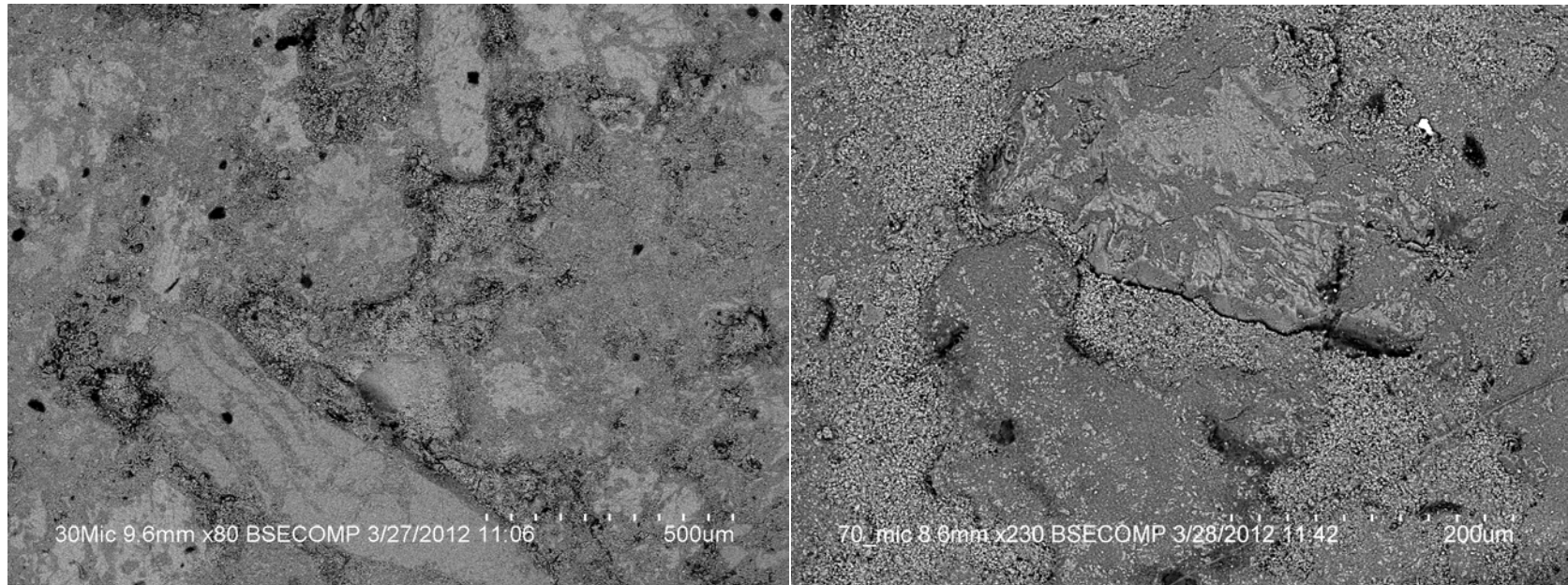
Figure 4. Synthetic carbonate samples characterized by different grain/micrite ratio and single-type porosity (i.e., microporosity).