Geology-guided pore space quantification for carbonate rocks

Mohammad Reza Saberim models the velocity on 23 core samples from a carbonate province by taking into account their pore structure variations, which will be linked to the formation processes of these carbonate rocks.

Introduction
The correlation between velocity and porosity or even density in carbonate rocks is normally highly scattered. This scattered pattern is an indication of a high degree of petrophysical heterogeneity within the mineral matrix and can make it more difficult to model and predict the acoustic behaviour of carbonate rocks compared to siliciclastics. This difficulty increases uncertainty in velocity prediction and is normally attributed to the heterogeneity of carbonate rocks and the complexity of their pore structure, which, furthermore, can be related to the carbonate forming processes (e.g. Rafavich et al., 1984; Anselmetti and Eberli, 1993, 2001; Saberi, 2010). The carbonate forming process starts from a wide spectrum of depositional environments and is followed by various post-depositional processes. This results in the pore structure of carbonate rocks being highly diverse and more complex compared to siliciclastic and in turn manifests the highly scattered behaviour of velocity-porosity trends (Anselmetti and Eberli, 1993). Therefore, determining pore geometry is a main requirement for carbonate rock characterization.

One of the major challenges in seismic characterization of carbonate reservoirs is establishing a quantitative link between pore geometry and elastic properties. Anselmetti et al. (1998) introduced a quantitative method for pore space evaluation based on thin section analysis to quantify and characterize carbonate micro-porosity. However, pore type interpretation from thin sections gives a non-unique subjective (interpreter-dependent) description of the pore space, and, therefore, cannot be related consistently with variations in elastic properties. On the other hand, inversion of seismic velocities or well-log data for pore structure modelling (e.g. Cheng and Toksöz, 1979; Sun and Goldberg, 1997; Yan et al., 2002), is purely mathematical and difficult to link with the complex geological and reservoir properties observed in carbonate reservoirs. In this regard, inclusion-based models, such as Kuster and Toksöz (1974), Differential Equation Medium (DEM) (Nishizawa, 1982) and self-consistent approximation (SCA) (Berryman, 1980a, b) which assume rock as an elastic matrix containing some inclusions (representing the pore space by using the pore aspect ratio) seem applicable for modelling pore space variations within carbonate rocks (Saberi,

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concluded that carbonate rocks with large and simple pores behave more stiffly and hence faster than rocks with small and complex pore systems. This complexity in carbonate pore structure (existence of different pore types) and related sensitivity to pressure changes brings more challenges and uncertainties to their elastic modelling. This is also one of the main reasons why applying the Gassmann (1951) fluid substitution model to carbonates is questionable (e.g. Marion and Jizba, 1997; Wang, 2000; Baechle et al., 2009; Xu and Payne, 2009). As a matter of fact, Gassmann assumes that pore space is connected and different forms of pore shapes (such as thin cracks along with stiffer pores, etc.) and saturations (such as patchy saturation) can validate or violate this assumption. This means that Gassmann may give overestimated, underestimated or even accurate elastic changes due to different fluids based on the carbonate’s pore system.

The objective of this paper is to review the observed velocity behaviour on 23 core samples from a carbonate province in order to model their velocity by taking into account their pore structure variations, which will be linked to the formation processes of these carbonate rocks.

Pore structure of carbonates

Anselmetti and Eberli (1999) report that carbonate rocks, having only intergranular and intercrystalline porosity, show little or no deviation in their P-wave velocity from the time-average equation of Wyllie et al. (1956),

\[
\frac{1}{V_p} = \left(1 - \Phi \right) \frac{1}{V_{p,m}} + \frac{\Phi}{V_{p,g}}
\]

(1)

Figure 2

Cross plot of well log porosity versus sonic P-wave velocity and their velocity deviation curve for wells A (a) and B (b), obtained by the subtraction of Wyllie time-average velocity model (solid blue line) from the measured sonic P-velocity. The scattering in the velocity deviation is very high for both wells and is normally attributed to different pore shapes.
changes (Saberi, 2010). This combination of various depositional
environments with different solidification paths can generate
different scenarios for the observed complexity in carbonate
pore systems. This combined effect can be observed through the
study of the link between carbonate depositional environments
and velocity changes. This infers that we should expect more
similarity in carbonate velocities from the same depositional
environments as has already been observed by Anselmetti and
Eberli (1993) who reported different velocity behaviour for
platform carbonates compared to basin and slope carbonates.

The same concept has been examined at two exploration wells
(wells A and B) penetrating a carbonate sequence within different
depositional environments. Figure 2 shows the porosity-velocity
crossplot for these two wells along with a time-average equation
calculated for existing mineralogy (Calcite, Dolomite, Anhydrite,
Quartz and Clay) mixed with brine. Both wells show a high
dynamic range of data on the crossplot. It can also be noted
that velocity-porosity trend changes with increasing porosity.
Furthermore, the velocity deviation curve has been calculated
by subtracting the time-average velocity from the measured
velocity at each sampling point. It can be seen that this velocity
deviation curve does not show a consistent behaviour with the
depth increment, making it difficult to build a reliable pore model
accordingly. This can be related to the background assumptions
of this heuristic model, which make it suitable for fluid-saturated
rocks with relatively uniform mineralogy under high differential
pressure (Mavko et al., 1998). This infers that pore model predic-
tion can be erroneous using only the time-average curve for rocks
with some degree of complexity. Therefore, there is a need for

where the subscripts \( m \) and \( f \) denote matrix and fluid, respec-
tively.

They explained that frame-forming pore types such as intra-
frame porosities (stiff pores) cause a positive deviation from
equation (1), while the effects of microcracks (weak pores) cause
a negative deviation. Figure 1 illustrates this concept of velocity
variations due to pore structure using the time-average equation of
Wyllie et al. (1956). Furthermore, this concept was used to define a
pore-model using inclusion-based models (e.g. Saleh and Castanga,
2004; Kumar and Han, 2005). This is especially applicable in
carbonate rocks in which different pore shapes make their elastic
response more complex. With this method, it is possible to use
only two pore types (interparticle/stiff or interparticle/crack) in the
modelling procedure out of the three main pore types (interparticle,
stiff and crack). This means that each modelling point can have a
maximum of two pore types, and the same sampling point cannot
have both crack and stiff pores together. We know that geologically
this is not true and applying such a concept can introduce some
errors during rock physics modelling. This constraint mainly comes
from having only the Wyllie time-average as the reference curve and
comparing all data points with only this curve. Therefore, defining a
second reference curve can help with the increasing number of pore
classes for a single modelling point. In this paper, defining a second
curve to define a pore-model will be investigated in more detail.

Environmental trend curve

The complexity of the carbonate rock’s pore system is normally
attributed to the depositional environment in which carbonate
rocks are deposited and have undergone subsequent diagenetic

Figure 3 Cross plot of well log porosity versus sonic
P-waves velocity and their velocity deviation curve
for wells A (a) and B (b) colour-coded for different
depositional environments.
data can help with a better velocity versus porosity relationship. This can be linked to the pore type evolution paths as noticed earlier by Anselmetti and Eberli (1993, 1996, and 2001). Here, the environmental trend (ET) term is defined as the 2nd order polynomial curve-fit to the log-data for each depositional environment. In general, environmental trend curves should express better the actual average velocity for a given porosity (compared with the time-average curve) for the given depositional environment. Because porosity and pore type evolutions are related to the depositional conditions and post depositional history, it seems relevant to expect different velocity-porosity trends for different depositional environments. Now, this curve in addition to the time-average curve can help to define a more geology-dependent pore-model.

Defining pore model and discussion
Currently, the Wyllie time-average curve is commonly used as the reference curve to define a pore-model consisting of an interparticle pore plus a stiff or crack pore type. The existing misfit for determining pore aspect ratios using only this curve infers that this model is incomplete to represent rocks with complex pore geometries such as carbonate rocks. Therefore, including a second curve is proposed to account for the existence of extra

Figure 4 Cross plot of well log porosity versus sonic P-wave velocity and their velocity deviation curve for wells A (a) and B (b) for each separated depositional environments.
pore types, which are not part of the reference pore model (i.e. time-average curve). This second curve, named as the environmental trend (ET), corresponds to the observation of the data. It is defined as the best fitted line across the velocity-porosity crossplots for different depositional environments on the well data. ET is a better representative of the velocity versus porosity behaviour of a given sediment, as porosity and pore type evolutions are normally attributed to the depositional conditions and their post-depositional history. This paper proposes the use of the environmental trend to estimate the necessary perturbations to be added to the TA model response instead of elaborating a complex modelling with a variety of porosities. By introducing the second reference curve in the workflow for characterizing pore aspect ratios, we are able to define more aspect ratios within the pore type spectrum by extending the TA response for higher or lower velocities. In fact, by using only the time-average approach, for each sampling point, we can account for a maximum of two pore types, but by complementing the model response with the environmental trend, we can increase this number to four pore types.

Figure 5 shows different steps for defining a pore model using these two curves. The process starts by using the Wyllie time-average curve following the Kumar and Han (2005) procedure to define a pore model for each sampling point. This pore model contains a reference pore (compared with the Wyllie curve) and some stiff or crack pores (a maximum of two pore types). Then, the environmental trend curve for each depositional environment is used as the second reference curve to account for a larger number of pore types. Note that stiff or crack pores are added to the previous pore model (from the Wyllie curve) if the sampling point is located above or below the ET curve, respectively. Figure 5 explains the procedure for a point between the Wyllie time-average curve and the environmental trend curve. This point is located above the Wyllie curve so that some spherical inclusions (stiff pores) are added to the pore model spectrum, but at the same time it is below the environmental trend, and as a result, some cracks are also added. The final pore model is a spectrum of different pore types with interparticle, stiff and soft pore types. This approach enables us to add different pore types to describe a complex pore structure within carbonates as it means we can define both stiff and crack pores for the same sample.

This workflow is applied on 23 core-plugs (with ultrasonic velocities) from our carbonate data set. These core plug samples

![Figure 5](image_url)
Conclusion

Carbonate rocks show a wide range of highly variable velocity patterns for a given porosity. This scattered behaviour is normally attributed to their complex pore structure which can be tracked down to their depositional and post-depositional environments. Therefore, having geological knowledge about how carbonate rocks form can be a great advantage for modelling their acoustic behaviour. The current approach for modelling pore aspect ratio in carbonates relies only on the Wyllie time-average as a reference point and on that basis attempts to capture complex pore structure in carbonates using a maximum of two aspect ratios. The observed misfit on the velocities indicates that this model alone is not capable of capturing all of the existing pore types in a rock with a complex pore system. It is possible to add a second reference curve in the pore type calculation workflow in order to perturb the time-average response and extend the number of pore aspect ratios. This second curve represents data observation and allows for control of the necessary perturbations on the time-average results. It is defined on the velocity-porosity crossplot using well log data and expresses the average (background) velocity-porosity behaviour for the given depositional environment. The proposed workflow are taken from Wells A and B with porosities ranging from less than 1% to more than 25% and permeability up to 30 mD within a large variety of lithofacies consisting of a mixture of different minerals (dolomite, calcite, quartz and anhydrites with admixtures of clay and organic materials). The modelling procedure started by defining the environmental trend curves for each depositional environment. Then, these curves in addition to the time-average curve are used to define a geology-dependent pore-model using self-consistent approximation following the procedure given in Figure 5. Here, the pore type volume fractions are determined by averaging the best fitted volume fraction for both P- and S-wave velocities (Saberi, 2010). Finally, these pore volume fractions and their aspect ratios are used to model both P- and S-wave velocities and the results are compared with ultrasonic velocities. Figure 6 shows this comparison between ultrasonic measurements and modelling results. It can be seen that a good prediction for both P- and S-wave velocity is modelled by using the same pore model. These pore models are calibrated using depositional environments, and can make a more direct link with the actual subsurface geology which is heterogeneous in carbonate rocks.
has been implemented on a complex carbonate platform with a large range of mineralogy to define its pore model. This workflow assists with defining a geology-oriented pore model consisting of interparticle, stiff and crack pores with greater flexibility to accommodate geological information.

**Data and materials availability**

This paper was part of the author’s PhD thesis published in 2010 and the data are the same as in his PhD thesis.

**References**


