

Geology-guided pore space quantification for carbonate rocks

Mohammad Reza Saberi¹ 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,

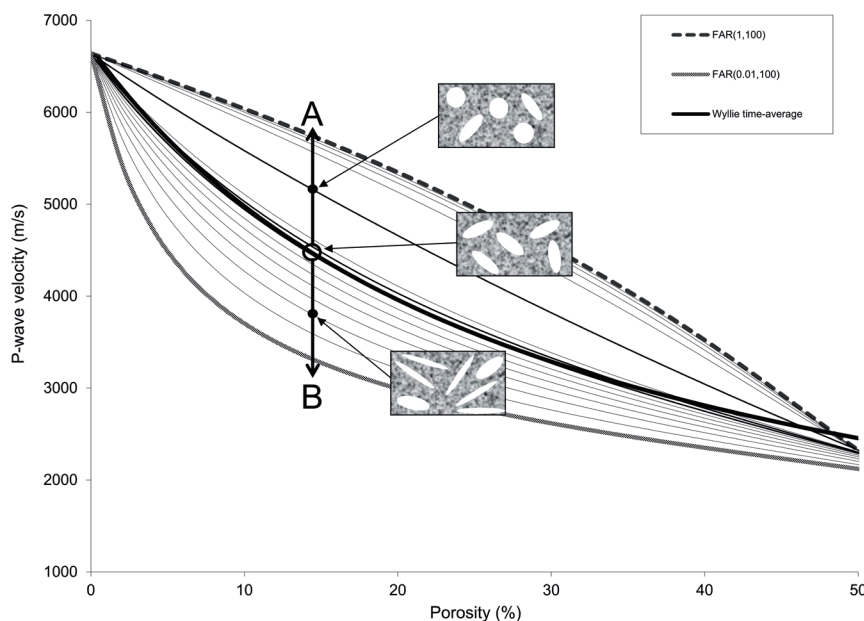


Figure 1 Modelling P-wave velocity variations with changes in porosity using the Wyllie time-average equation (solid black line) and self-consistent approximation (SCA) model using different pore aspect ratios (grey lines and dashed black line). Here, the time-average curve is assumed as the reference curve which passes through samples with interparticle porosity. The velocities that are higher than this velocity (given by the time-average equation) are increased by adding some fractions of intra-frame porosity (stiff pores) (towards A). The velocities lower than this velocity (given by the time-average equation) are decreased by adding some fractions of crack porosity (very low aspect ratio pores) (towards B). Here, the modelled curves using SCA for different aspect ratios are shown with the name of FAR (fixed aspect ratio). FAR (a , $f(a)$) expresses pore geometry based on the aspect ratio (a) and its volume fractions ($f(a)$), for instance, FAR(1,100) shows the scenario that all of the porosity (100%) of the rock has an aspect ratio equaling one.

¹ CCG

* Corresponding author, E-mail: Reza.Saberi@cgg.com

DOI: 10.3997/1365-2397.fb2020018

2010). Within these models, fixed values of pore aspect ratios are often used for velocity modelling. However, the study by Yan et al. (2002) showed that elastic moduli have non-linear behaviour with respect to the changes in pore aspect ratios. This indicates the limitation of using fixed pore aspect ratios to small depth intervals over which lithology may be considered uniform. One commonly used assumption for modelling pore structure effects on acoustic properties in carbonates uses the ‘velocity deviation’ term defined by Anselmetti and Eberli (1999) (e.g. Saleh and Castagna, 2004; Kumar and Han, 2005). This term is defined as the differences between the measured velocities and the time-average equation of Wyllie et al. (1956). This quantitative method highlights intervals with frame-forming pore types (stiff pores) with strong positive deviations while interparticle and micro-porosities (weak pores) make almost zero or negative deviations. However, the weak correlation for velocity estimates using porosity and digital image parameters for aspect ratios, as mentioned by Eberli (2009), indicates that aspect ratios may not be the only parameter responsible for variations in acoustic velocities. Weger (2006), Colpaert (2007) and Eberli (2009) suggested pore size (DOMsize) and pore space complexity (P/A) as two other parameters that may give a better explanation for the scattering observed on the velocity-porosity crossplots. DOMsize is the maximum pore size needed to occupy half of the pore space on a given thin section, while P/A is the sum of the pore space perimeter over the sum of the pore space area. Therefore, these two parameters should be able to capture the pore system for numerical elastic modelling (Weger, 2006; Colpaert, 2007). Colpaert (2007) along with Weger (2006) evaluated the impact of these parameters on carbonate velocity behaviour. They

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),

$$\frac{1}{V_P} = \frac{(1-\Phi)}{V_{P,m}} + \frac{\Phi}{V_{P,f}} \tag{1}$$

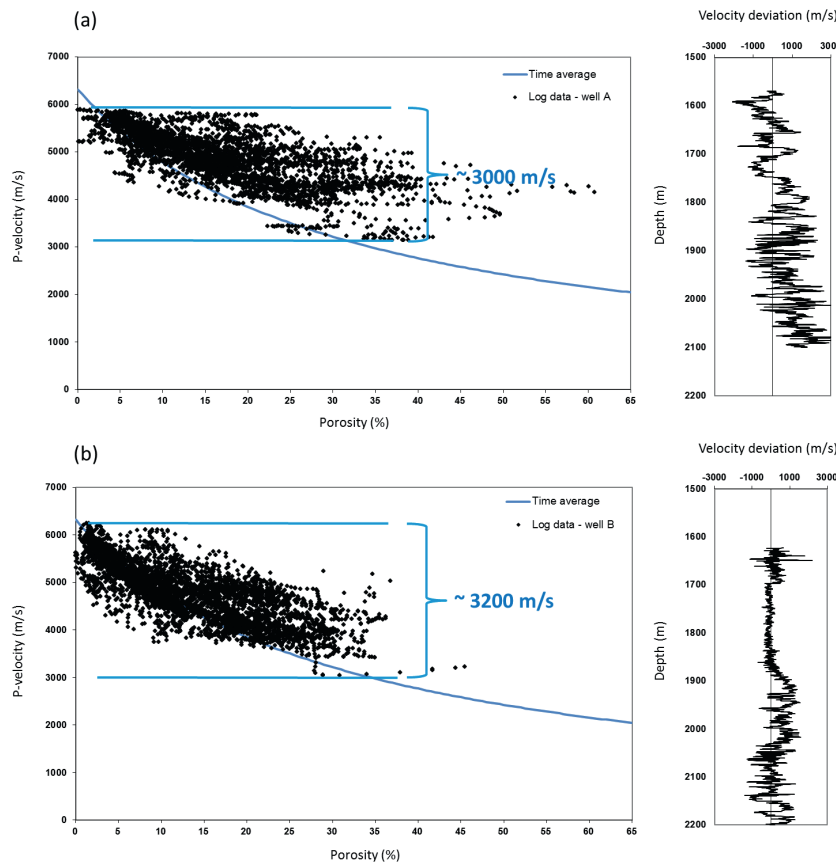


Figure 2 Cross plot of well log porosity versus sonic P-wave velocity and their velocity deviation curve for wells A (a) and B (b), obtained by the subtraction of Wyllie time-average velocity model (solid blue line) from the measured sonic P-velocity. The scattering in the velocity deviation is very high for both wells and is normally attributed to different pore shapes.

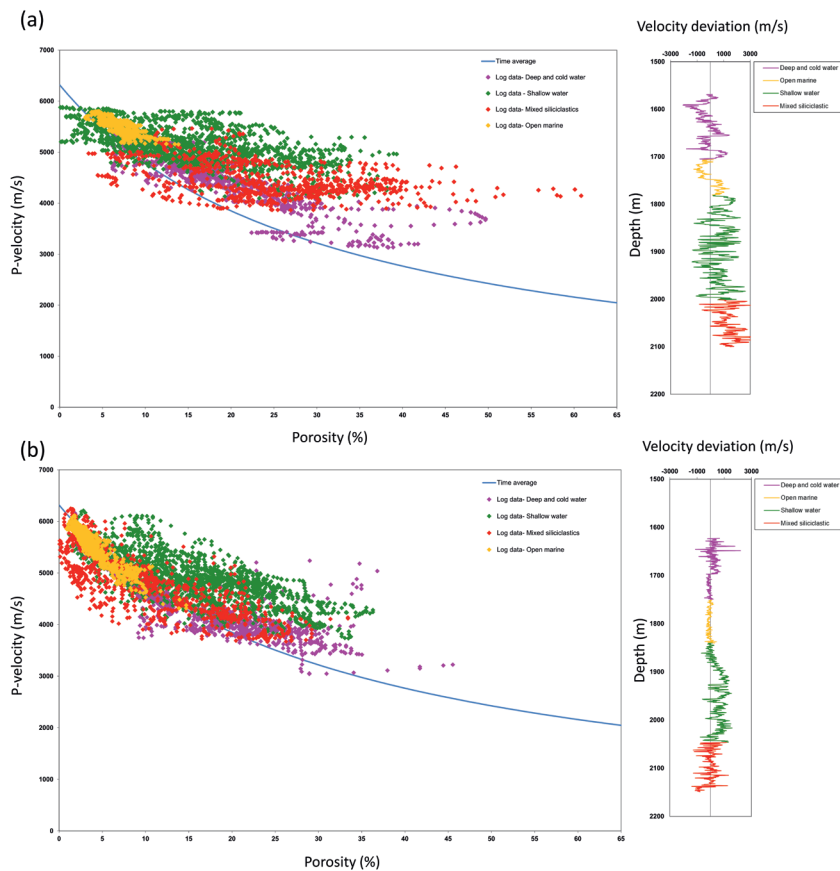


Figure 3 Cross plot of well log porosity versus sonic P-wave velocity and their velocity deviation curve for wells A (a) and B (b) colour-coded for different depositional environments.

where the subscripts m and fl denote matrix and fluid, respectively.

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

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 prediction can be erroneous using only the time-average curve for rocks with some degree of complexity. Therefore, there is a need for

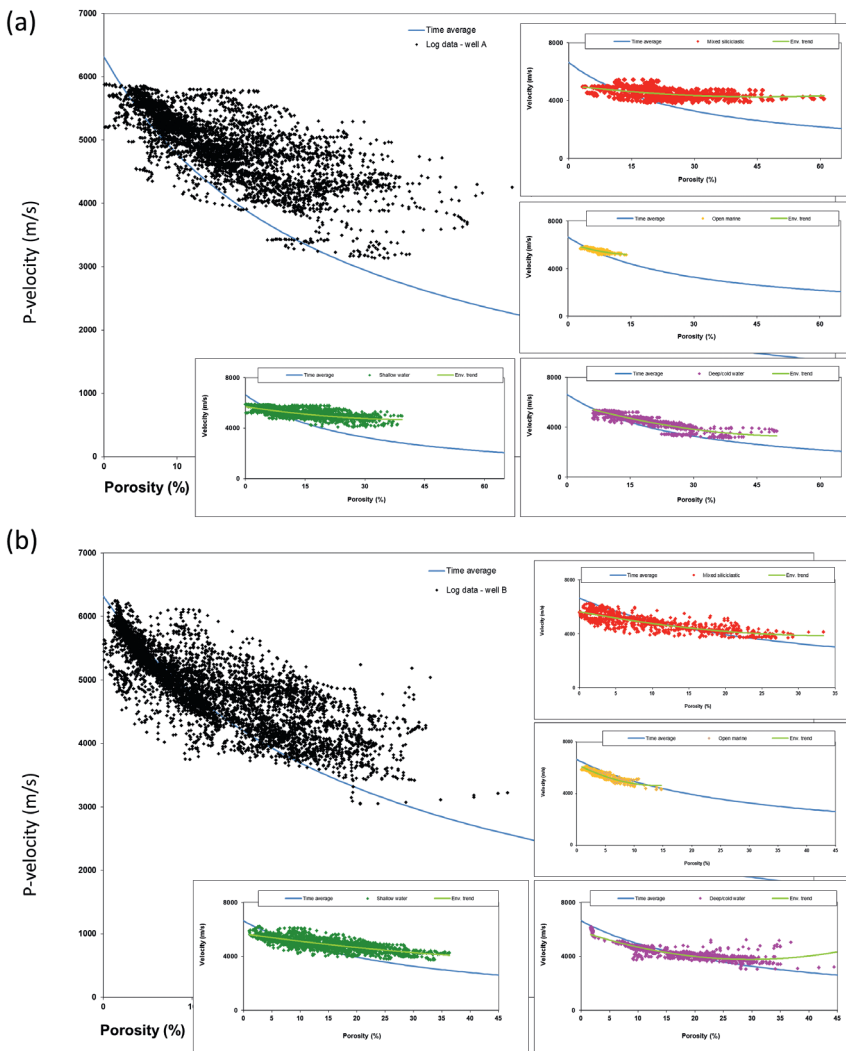


Figure 4 Cross plot of well log porosity versus sonic P-wave velocity and their velocity deviation curve for wells A (a) and B (b) for each separated depositional environments.

a geologically driven approach to calibrate the determined pore models from the Wyllie time-average based on the actual subsurface microstructure. In this regard, depositional environment can provide a suitable tool for such purposes as shown in Figure 3. Figure 3 depicts the same crossplots in Figure 2 but colour-coded with four different depositional evolution stages introduced by Ehrenberg et al. (1998a, b) for these two wells. Studies by Ehrenberg et al. (1998a, b) on these two wells distinguish between four different stages of depositional evolution: mixed siliciclastic and carbonate, shallow water, open marine and deep/cold water environments. Each of these four depositional evolution stages is characterized by a different style of diagenesis and porosity development (Ehrenberg et al., 1998a, b). This means that they have gone through different pore type evolution paths which require different reference equations for different pore stiffnesses. Figure 3 clearly explains how these depositional environments affect the velocity deviation curve with a distinct behaviour for each of them. This classification, furthermore, reduces the observed scattering in the porosity-velocity crossplot (Figure 4). Figure 4 depicts each depositional environment and compares it to the Wyllie time-average and the best fit on the well log data (named as environmental trend). This Figure clearly shows how applying the depositional environment concept on our well log

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

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

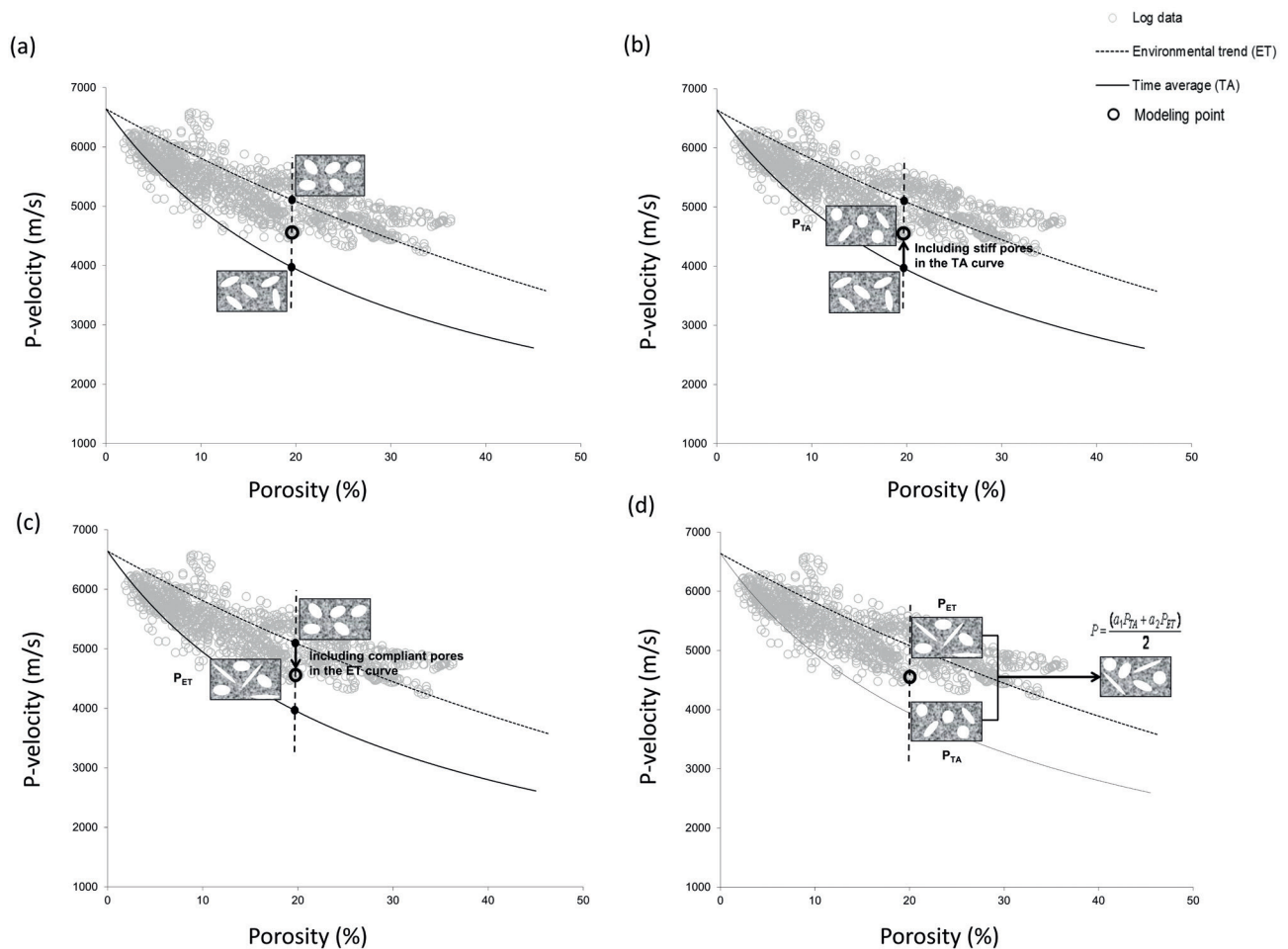


Figure 5 The crossplot of P-wave velocity versus porosity for pore space modelling purposes: (a) estimating pore space modelling using only time-average (TA) and environmental trend (ET) as referential curves, (b) modelling point obtained by including stiff pores in the TA model (P_{TA}) using SCA (c) modelling point obtained by including compliant pores in the ET model (P_{ET}) using SCA (d) final pore-model (P) which includes intraparticle, stiff and crack pores and their volume fractions obtained by the weighted average between the volume fraction of the pore models calculated at (b) and (c). Note that the ET curve, which represents the exponential fit on log data for different depositional environments, attempts to correct the TA model for the possible effects of formation processes on pore geometry such as compaction, cementation and dissolution. This helps with characterizing pores with complex shapes by introducing more pore types into the pore-model. It means that our rock physics model can use both stiff and compliant pores for modelling purposes.

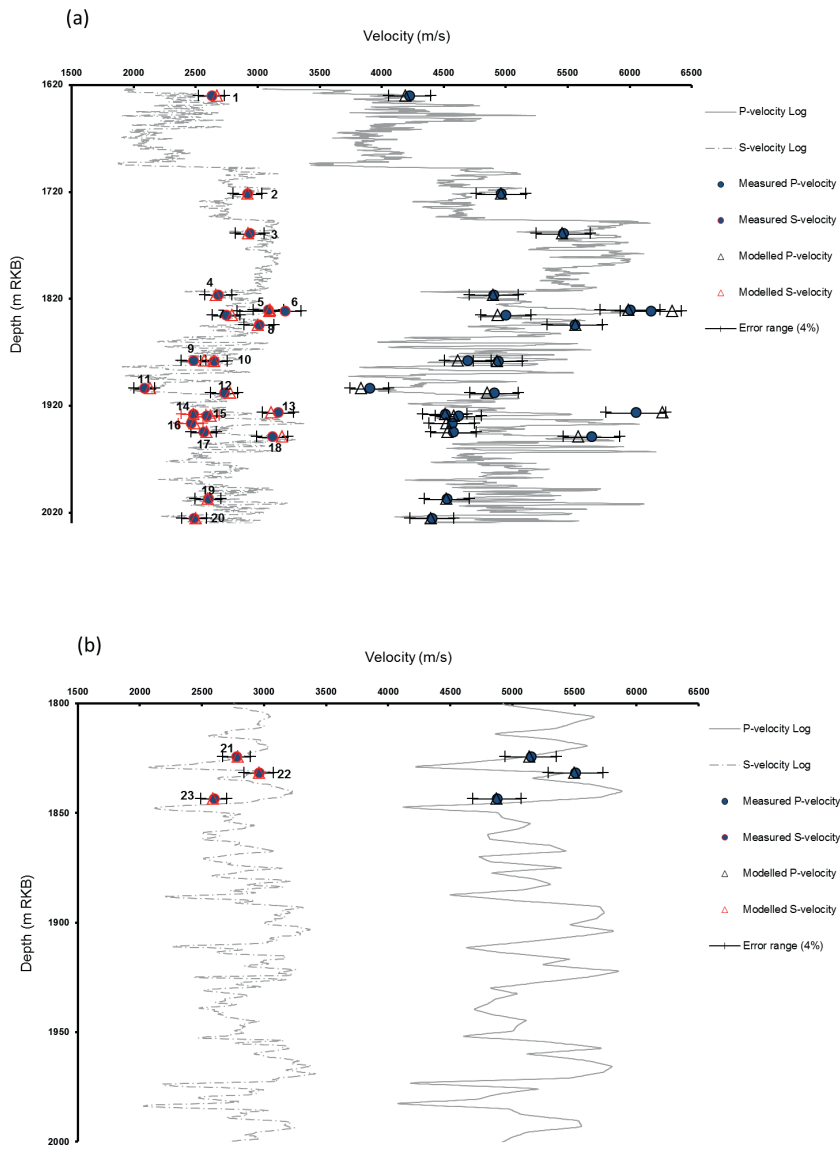


Figure 6 P and S velocity modelling for 23 multi-mineral brine-saturated core-plugs on Wells A (a) and B (b). The environmental effect is incorporated into the pore-model by following the workflow of Figure 5. The numbering of 23 samples is shown on the sonic S-wave velocities.

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 (Saber, 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.

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

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

- Anselmetti, F.S. and Eberli, G.P. [1993]. Controls on sonic velocity in carbonates. *Pure and Applied Geophysics*, **141**, 287-323.
- Anselmetti, F.S. and Eberli, G.P. [1996]. Sonic velocity in carbonate sediments and rocks. In: Palaz, I. and Marfurt K.J. (Eds.) *Carbonate Seismology - Geophysical Development Series*, **6**, 53-74.
- Anselmetti, F.S. and Eberli, G.P. [1999]. The velocity deviation log: A tool to predict pore type and permeability trends in carbonate drill holes from sonic and porosity or density logs. *The American Association of Petroleum Geologists*, **83**(3), 450-466.
- Anselmetti, F.S. and Eberli, G.P. [2001]. Sonic velocity in carbonates – a combined product of depositional lithology and diagenetic alterations. In: Ginsburg, R.N. (Eds.) *Subsurface geology of prograding carbonate margin - Great Bahama Bank: results of Great Bahamas Drilling project*, **70**, 193-216.
- Berryman, J.G. [1980a]. Long-wavelength propagation in composite elastic media I. spherical inclusions. *Journal of Acoustic Society of America*, **68** (6), 1809-1819.
- Berryman, J.G. [1980b]. Long-wavelength propagation in composite elastic media II. Ellipsoidal inclusions. *Journal of Acoustic Society of America*, **68** (6), 1820-1831.
- Baechle, G.T., Eberli, G. P., Weegar, R.J. and Massafiero, L. [2009]. Changes in dynamic shear moduli of carbonate rocks with fluid substitution. *Geophysics*, **74**(3), E135-E147.
- Cheng, C.H. and Toksöz, M.N. [1979]. Inversion of seismic velocities for the pore aspect ratio spectrum of a rock. *Journal of Geophysical Research*, **84** (B13), 7533-7544.
- Colpaert, A. [2007]. Geophysical characterization of Carboniferous-Permian carbonate platforms in the Barents Sea based on 3D-seismic data analysis and rock physics modeling. *PhD thesis*, University of Tromsø, Norway.
- Eberli, G.P. [2009]. Combining rock physics and sedimentology for identifying subtle exploration models in carbonates. *Sound of Geology Workshop*, Abstracts.
- Ehrenberg, S.N., Nielsen, E.B., Svånå, T.R. and Stemmerik, L. [1998a]. Depositional evolution of the Finnmark carbonate platform, Barents Sea: results from well 7128/6-1 and 7128/4-1. *Norwegian Journal of Geology*, **78**, 185-224.
- Ehrenberg, S.N., Nielsen, E.B., Svånå, T.R. and Stemmerik, L. [1998b]. Diagenesis and reservoir quality of the Finnmark carbonate platform, Barents Sea: results from wells 7128/6-1 and 7128/4-1. *Norwegian Journal of Geology*, **78**, 225-252.
- Gassmann, F. [1951]. Über die elastizität poröser medien. *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich*, **96**, 1-23.
- Kumar, M. and Han, D.-H. [2005]. Pore shape effect on elastic properties of carbonate rocks. *Society of Exploration Geophysicists Technical Program*, Expanded Abstracts, 1477-1480.
- Kuster, G.T. and Toksöz, M.N. [1974]. Velocity and attenuation of seismic waves in two phase media: Part I. Theoretical formulations. *Geophysics*, **39**, 587-606.
- Marion, D. and Jizba, D. [1997]. Acoustic properties of carbonate rocks: Use of quantitative interpretation of sonic and seismic measurements. In: Palaz, I. and Marfurt K. J. (Eds.) *Carbonate Seismology - Geophysical Development Series* **6**, 75-93.
- Mavko, G., Mukerji, T. and Dvorkin, J. [1998]. *The rock physics handbook*. Cambridge University Press.
- Nishizawa, O. [1982]. Seismic velocity anisotropy in a medium containing oriented cracks. Transversely isotropic case. *Journal of Physics of the Earth*, **30**, 331-347.
- Rafavich, F., Kendall, C.S.C. and Todd, T.P. [1984]. The relationship between acoustic properties and the petrographic character of carbonate rocks. *Geophysics*, **49**(10), 1622-1636.
- Saberi, M.R. [2010]. An integrated approach for seismic characterization of carbonates. *Ph.D. Dissertation*, University of Bergen.
- Saleh, A.A. and Castanga, J.P. [2004]. Revisiting the Wyllie time average equation in the case of near-spherical pores. *Geophysics*, **69**(1), 45-55.
- Sun, Y.F. and Goldberg, D. [1997]. Estimation of aspect-ratio changes with pressure from seismic velocities. In: Lovell, M.A. and Harvey, P.K (Eds.) *Developments in Petrophysics. Geological Society Special Publication*, **122**, 131-139.
- Wang, Z. [2000]. The Gassmann equation revised: Comparing laboratory data with Gassmann predictions. In: Wang, Z., Nur, A. and Ebro, D.A. (Eds.) *Seismic and Acoustic Velocities in Reservoir Rocks*, 8-23.
- Wyllie, M., Gregory, A.R. and Gardner, G.H.F. [1956]. Elastic wave velocities in heterogeneous and porous media. *Geophysics*, **21**(1), 41-70.
- Xu, S. and Payne, M.A. [2009]. Modeling elastic properties in carbonate rocks. *The Leading Edge*, **28**(1), 66-74.
- Yan, J., Li, X.Y. and Liu, E. [2002]. Effects of pore aspect ratios on velocity prediction from well-log data. *Geophysical Prospecting*, **50**, 289-300.