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Integration of Rock Digital Images to Improve Carbonate Rock Physics Model of Offshore Sarawak

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Abstract: It has been recognized that carbonate reservoirs are one of the biggest reserved for hydrocarbon. Clearly, the evaluation of these reservoirs is critical. For accurate reservoir characterization and performance prediction from geophysical measurements, good understanding of geophysical response of different carbonate pore types is crucial. However, carbonate rocks are difficult to characterize due to their complex pore systems. The complex depositional environment and significant diagenesis process makes pore systems in carbonates far more complicated than in clastics. Therefore, it is difficult to establish rock physics model for carbonate rock type. In this study, we evaluate the possible rock physics model of 20 core plugs of a Miocene carbonate platform in Central Luconia, Sarawak. The published laboratory data of this area were used as an input to create the carbonate rock physics models. The elastic properties were analyzed to examine the validity of an existing analytical carbonate rock physics model. We integrated the Xu-Payne Differential Effective Medium (DEM) Model and the elastic modulus which was simulated from a digital carbonate rock image using Finite Element Modeling. The results of this integration matched well for the separation of carbonate pore types and sonic P-wave velocity obtained from laboratory measurement. Thus, the results of this study show that the integration of rock digital image and theoretical rock physics might improve the elastic properties prediction and useful for more advanced geophysical techniques (e.g., Seismic Inversion) of carbonate reservoir in Sarawak.

Key words: Elastic modulus, elastic properties, geological models

INTRODUCTION

Despite all the efforts and resources of new geological models, high resolution data and development of new technologies, the predictions of carbonate properties and fluid contents from seismic are still a difficult challenge. A great spatial variability of parameters e.g., porosity and permeability are the main problems that cause the prediction more complicated than in clastics. The Rock physical models that take into consideration of these specific carbonate rocks features can constrain quantitative seismic interpretation e.g., AVO and time lapse analysis approaches.

As distinct from sandstones, in carbonate systems, the combined effect of variations in depositional facies and diagenetic alteration plays a key role in controlling the variations in sonic velocities and acoustic impedance, which makes the seismic response of these rocks hard to interpret and understand. Carbonate pore types are considered the key factor causing significant variations in permeability and elastic properties (Eberli *et al.*, 2003;

Bashah and Pierson, 2012). Dolomitization, the process of calcium to magnesium substitution, is one of the most important processes of the reservoir properties degradation. Dolomitization usually decreases porosity (Lucia, 1999) and increases bulk and shear moduli. Because of this complex behavior, in terms of geological models, it is important to establish the main trends.

The measurements from laboratory are crucial and importance for hydrocarbon exploration, especially in carbonate reservoir. Even the robust and sophisticated geological models which are formed from well logs and seismic datasets that improve the information for every year need to be confirmed and validated experimentally in the laboratory. The best way to achieve this goal is through laboratory experiments in controlled conditions. Advances in technology also make the laboratories better equipped and new valuable information can be obtained to help to understand the ultimate datasets. The number of laboratory ultrasonic measurements in carbonates will increase and to address this demand, new and more efficient theoretical models need to be employed to

explain this data. Finally, the understanding of the physical properties of carbonates, measured or estimated (but well calibrated), are fundamental for the quantitative seismic interpretation of the complex carbonate reservoirs were analysed.

The proposed study seeks to evaluate and analyze the published laboratory measurements data of elastic properties on reservoir carbonate samples in offshore Sarawak (Bashah and Pierson, 2012) and develop the appropriate workflows that can be possibly used in log analyses and quantitative seismic interpretation. Since the elastic properties of carbonates highly depend on the pore type and shape of the carbonate rocks (Bashah and Pierson, 2012; Eberli *et al.*, 2003; Weger *et al.*, 2004; Kumar and Han, 2005). In this study a different approach was proposed to improve the rock physics model. We integrated the information of the microstructure of carbonate rock to the rock physics model. The microstructure of carbonate rock was downloaded from Andra *et al.* (2013a). The microstructure is analyzed using high quality X-Ray micro-CT to construct realistic dual-nature porosity models, quantify stiffness and compliance porosities and extract elastic parameters for seismic waves. With this approach the use of laboratory analysis information, constrained by realistic geological information was maximized.

METHODOLOGY

Differential effective medium model: The combined effect of variations in depositional facies and diagenetic alteration occurred during intense geological processes cause carbonate rocks to develop wide variations of pore types, such as interparticle, intercrystal, moldic, vuggy, intraframe and microcracks (Lucia, 1999). Although this classification is useful for characterizing petrophysical properties, relating these microstructures and trends to geophysical responses and further geophysical method application such as seismic inversion are very challenging. From previous geoscientist observation, normally, vuggy pores are very rigid and less affected by seismic wave propagation, while cracks are effective to reduce velocities in carbonates (Eberli *et al.*, 2003).

Xu and Payne (2009) demonstrated that Xu and White (1995) model for shaley sandstones can be extended to predict velocities in carbonate rocks. Following Xu and Payne’s rock physics modeling approach for carbonates, we mixed minerals present in the rock using Voigt-Reuss-Hill averages. Differential Effective Medium (DEM) scheme is used to calculate the dry effective bulk and shear moduli for different geophysical pore types represented by the pore aspect ratio.

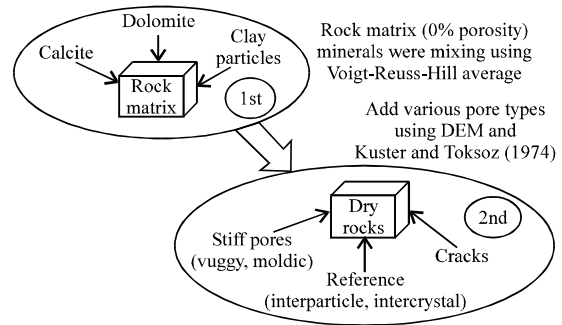


Fig. 1: Structural diagram of DEM to build carbonate rock physics model in the present study (modified from Xu and Payne (2009))

We abstractly represent seismic velocities in carbonate reservoir rocks by using three geophysical pore types as in Fig. 1: (1) Reference pores, which mainly consist of inter-particle pores and is considered the dominant pore type in carbonate rocks, (2) Stiff pores, which represent moldic and vuggy pores, which are usually formed as a result of dissolved grains and fossil chambers. (3) Cracks, which can occur due to differential compaction, faulting and solution collapse in carbonates (Lucia, 1995; Xu and Payne, 2009; Kumar and Han, 2005).

Each pore component is incrementally added to the rock matrix to calculate the elastic properties of the resultant effective medium. One versatile feature of the Xu-Payne model is that individual pore components can be included into the model such that they are either isolated, or, in perfect fluid connectivity with the remaining pore space. The pore space model is calibrated using a cross-plot of P-wave velocity against porosity (Kumar and Han, 2005).

Figure 1 shows how can we create our carbonate rock physics model on dry rock (rock which not contained fluids). The first step is using a mixing law (the Voigt-Reuss-Hill average) to mixed the minerals which are present in the rock. The dominant minerals for carbonate rocks are usually calcite and dolomite. Last step is to incorporate differential effective media theory and Kuster and Toksoz (1974) theory to include type of pores (Moldic, Interparticle and Microcracks) and take into account the mechanical interaction between pores. The result of the calculation is the effective elastic properties of Dry Rock. Figure 2 shows the predicted effect of pore type on P-wave velocity, the reference line for mixed minerals which contains interparticle and intercrystal pore types are also incorporated on the plot.

In Fig. 2 the solid matrix was assumed with dominant mineral in calcite plus clay particles. The

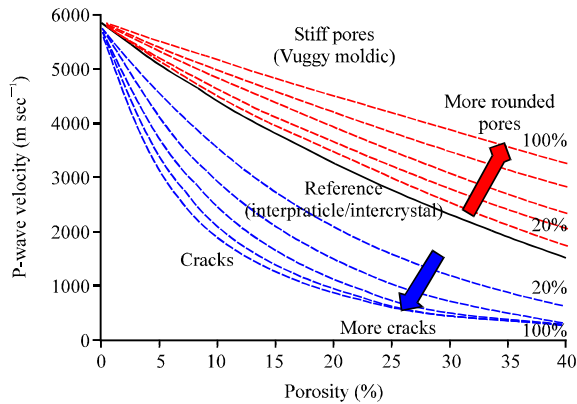


Fig. 2: DEM results for different percentage pore types on P-wave velocity

average Voigt-Reuss-Hill was used to calculate the minerals average of carbonate rocks for P-wave velocity. The reference represents a system with interparticle or intercrystal pore types. The curves below the reference curve represent systems with increasing percentage of cracks pore type. The curves above the reference curve represent systems with increasing percentage of stiff pore (vuggy/moldic).

Numerical methods to compute the physical properties:

The numerical computations of the physical properties of rock were computed on a 3D CT-scan image of intercrystal carbonate rock. The data used in this proposed work was taken from a benchmark shared dataset from Andra *et al.* (2013b). The physical properties, e.g., porosity (total, connected and unconnected), absolute permeability and formation factor, were re-simulated and calculated using AVIZO commercial software. As for the calculation of the elastic properties were taken from Andra *et al.* (2013b) study.

Porosity: Three different porosities are reported: Total porosity, percolating (connected) porosity and isolated (unconnected) porosity. Connected or percolating porosity is the fraction of total porosity that available to flow. The fraction of total porosity that unable for flow is categorized as unconnected or isolated porosity. The following relations hold for porosities of CT-Scan image:

$$\phi_{tot} = \phi_{perc} + \phi_{iso} \tag{1}$$

Absolute permeability: The Lattice Boltzmann Method (LBM) for fluid simulation is an appropriate choice for these cases. This method is a robust technique that simulates flow according to simple rules governing local

interactions between individual particles and recovers the Navier-Stokes equations at the macroscopic scale.

Boltzmann equation solved by counting particle density distribution at time *t* and location of *r*. From the local flux, a volume averaged flux can be calculated. Then, the absolute permeability is computed in a manner analogous to a laboratory measurement: A pressure head or body force is directly applied to a digital sample. The resulting fluid flux is computed and permeability is calculated according to the Darcy’s law:

$$k = \frac{\langle Q \rangle}{\nabla P} \mu \tag{2}$$

The flow simulation is performed with pressure gradient (∇P) assigned across opposite faces of the 3D cube. Next, a volume averaged flux $\langle Q \rangle$ is computed from local flux and μ is the dynamic viscosity of the fluid.

Formation factor: The steady state electrical conductivity, or formation resistivity factor (*F*), of a brine saturated rock is governed by the Laplace equation:

$$\nabla \cdot J = 0 \tag{3}$$

$$J = \sigma_w \nabla \phi \tag{4}$$

Subject to the boundary condition $\nabla \phi \cdot n = 0$ on the solid walls (i.e., insulating walls). Where, *J* is the electrical current, σ_w is the electrical conductivity of the fluid that fills the pore space, Φ is the potential or voltage and *n* is the unit vector normal to the solid wall. Numerical solutions of the Laplace equation are obtained by a random walk algorithm or by a finite difference method.

The effective directional conductivities σ_i , *i* = x, y, z are computed by applying a potential gradient across the sample in *i*-direction. The directional formation resistivity factor *F_i* is the inverse of the effective electrical conductivity $F_i = \sigma_i / \sigma_w$. We define the average formation resistivity factor *F* as the harmonic mean of direction dependent formation factors.

Elastic properties: The finite element method described by Garboczi and Day (1995) has been implemented for calculation of elastic properties. The method uses a variational formulation of the linear elastic equations and finds the solution by minimizing the elastic energy using a fast conjugate-gradient method. The results are valid for quasi-static conditions or at frequencies which are sufficiently low such that the included pore pressures are in equilibrium throughout the pore space (Dvorkin *et al.*, 2011). The effective bulk and shear moduli are computed

assuming isotropic linear elastic behavior. The V_p and V_s are subsequently calculated using the simulated effective elastic moduli and the effective density according to:

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad (5)$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (6)$$

Inputs for the calculations are:

- A three-dimensional representation of the rock microstructure (a digital rock sample)
- Density (ρ) and elastic properties (K and μ) of each mineral composing the rock matrix
- Density (ρ) and elastic properties (K and μ) of the fluid present in the pore space

RESULTS AND DISCUSSION

The main objective of this study is to improve the elastic properties prediction on carbonate rock type by integrating pore type information, through rock physics (DEM) and rock digital image. If we successfully integrate pore types information with laboratory measurement and rock digital image, there is possibility to use seismic inversion on the Central Luconia carbonate area.

Pore type effect on elastic properties was examined and calibrating the pore geometry related parameters in effective medium based model then integrated with the effective elastic properties simulated on carbonate rock digital image. Figure 3 shows the calibration of pore geometry with P-wave velocity from laboratory measurement.

Next step, we examined and integrate the results on the computation of physical properties on rock digital image. Table 1 show the physical properties simulated on carbonate rock digital image.

Calculated V_p are integrated on the previous plot and shown in Fig. 4. Green line gives the best fit using Xu-Payne model with pore aspect ratio of 0.15. Red and blue dashed lines give the best fit with aspect ratio of 0.8 and 0.02, respectively. From the plot we can observe that the dominant pore types from 20 core plugs (grey dots) are stiff pores (vuggy/moldic). There are two data sets which, refer to red circles on Fig. 4, align with the reference plot (interparticle/intercrystal) pore types.

The green squares refer to the simulation of effective P-Wave velocities which were calculated using the information on Table 1. Clearly, the compliance difference

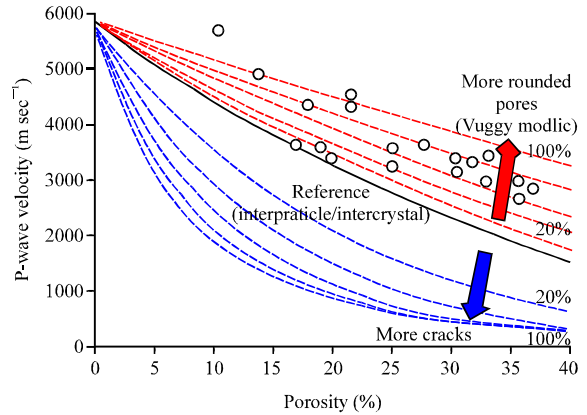


Fig. 3: Illustration of possible pore type effects on the P-wave velocity and porosity relationship. All of the data points are sonic velocity data from Bashah and Pierson (2012)

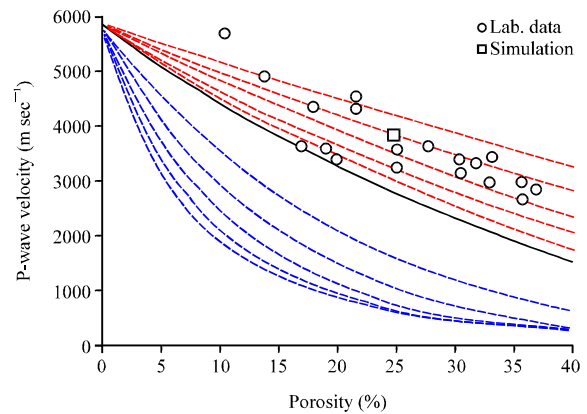


Fig. 4: Green circles are P-Wave velocities computed on 3D CT scan image of carbonate digital image. Grey dots are P-Wave velocities from laboratory measurement (Bashah and Pierson, 2012). Red and blue dashed line indicates vuggy give the best fit with aspect ratio of 0.8 and 0.02, respectively

Table 1: Simulation results for physical properties on carbonate rock digital images

Property	Image	Volume
Image volume (voxel*)	400 ³	1024 ³
Porosity (%)		
Conc.	23.55	22.05
Iso.	0.9	2.42
Bulk modulus (GPa)	24.8**	25**
Shear modulus (GPa)	14**	13.6**
Permeability (mD)	630.45	723
Formation factor	26	30

*Voxel: Volume pixels, **Data from Andra *et al.* (2013a)

for the total porosity of 24.7% and intercrystal pore type, the calculation of P-wave velocity is far above the reference line.

The fundamental reason of the difference was the input of the simulation which only uses pure calcite value for the simulation. As expected the results are faster than the reference line. The other aspect is there might not all the microstructures are resolved during the acquisition of CT-Scan data, since in carbonate the micropore/cracks might have the size of below 1 μm .

CONCLUSION

We have demonstrated that the integration of Rock digital image elastic properties simulation and Xu-Payne model is efficient for the use elastic properties prediction on carbonate rock type. The possible of using Gassmann's theory for fluid substitution on carbonate might lead on the possible geophysical pore fluid inversion that can be calibrated on log and seismic data on carbonate reservoir, especially in Sarawak. We use the rock physics modelling approach that takes into account three defined geophysical pore types and shown the possibility to bridge them to the bigger scale such as log and seismic responses.

A more comprehensive study that includes more samples with various pore types and similar porosity values need to be carried out. This can be done (if the core samples are not available) on digital rock images of cuttings and sidewall core plugs which cannot be used to properly on the laboratory for measurement. It can be done fast and several times partition, as shown in this work, we show that the simulation on 1024 and 400 cubes on the same data.

This approach is practical, easily repeatable (in real time) and can be used as an alternative method when core plug is not available. The possibility to use this method on chips, cuttings and rotary sidewall cores that routinely available from wells is also align to obtain elastic properties distribution information since these samples give good sampling intervals which almost cover whole depth of the wells. However, there is always uncertainty associated with geophysical pore type inversion results as it depends on many different factors: the quality of seismic data, number of wells, input AI and porosity volumes, shale content, fluid content, etc.

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