Rock physics model to determine the geophysical pore-type characterization and geological implication in carbonate reservoir rock

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Abstract. The pore geometry of carbonate reservoir consists of such heterogeneous, complex, variation types of pore structure and high chemical material reactivity. Rock physics modeling is applied in this study as it is an accurate, precise and practical method for the case of carbonate reservoirs. It is examined to determine the effect of carbonate reservoir geometry on the seismic wave velocity in carbonate field using fast DEM (Differential Effective Medium) model. We integrate measured logs and petrophysics data from gas-saturated carbonate reservoir. The results show that majority of pore geometry in the research area are interparticle pores and micro-cracks pores. The pore geometry interprets the effects of seismic wave velocity of carbonate reservoir in the study area, stiff pores or the increasing of $\alpha$ values will make the seismic wave velocity to increase rapidly and crack pores or the decreasing of $\alpha$ values will make the seismic wave velocity slower. Generally, we have worked in the common geological condition of carbonate reservoir rocks. In terms of aspect ratio value, our reservoirs controlled by overburden geological process. This indicated that fracturing is closely related to overburden and differential compaction, thus increasing the connection between separate vugs and enhancing permeability dramatically.

1. Introduction
Carbonate reservoir rocks are considered as a major host rock for hydrocarbon reservoirs, making up almost 60% of the proven reserves on the earth. They are obviously different from clastic/siliciclastic reservoirs due to the differences in their depositional environments and complicated diagenetic processes [1,2]. Through such high chemical reactivity of carbonate material, these rocks are constantly experiencing exquisite cementation, dissolution, and dolomitization, that strongly influenced by several factors such as water depth, temperature, and pressure. Such an intensive diagenetic history can alter the mineralogy and texture of the original framework, thereby causing carbonate rocks to exhibit wide variations in pore types, such as interparticle, inter-crystal, moldic, vuggy, intraframe and micro-cracks.

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Previous laboratory studies of carbonate reservoir rocks have shown that measured velocity-porosity data have a wide range of scattering cross-plots [3,4,5]. Carbonate rocks are well-cemented and grain contact elasticity are not considered as important parameters affecting the elastic properties of carbonate [6]. For a given mineral composition and fluid type, such scattering on velocity-porosity cross-plots could be mainly related to the pore-type effects [4]. In general, it is found that frame-embedded pores, such as moldic and vuggy pores, are round and very resistant to pressure changes. On the other hand, thin penny-shaped cracks tend to be flat and will have much lower stiffness, thus being easily affected by seismic wave propagation.

Different rock physics studies have incorporated the pore-type effect into predicting and modeling elastic properties in carbonate rocks. Pores in carbonate rocks are often modeled as ideal ellipsoidal inclusions which characterized by their aspect ratio (minor axis divided by major axis) by using a long-wavelength first-order scattering theory. The major constraint in this theory is that the ratio of porosity and aspect ratio should be less than or equal to 1. This means that for ellipsoidal cracks (aspect ratio is about 0.01), this theory can calculate effective media properties only up to a porosity of 1%. This limitation restricts the use of this model. In order to overcome the dilute concentration a differential effective medium (DEM) scheme [7,8] by inserting dry inclusions to obtain the effective properties of rocks. In this paper, we will discuss the effect of pore geometry (aspect ratio) to seismic velocity and the implication of geological interpretation in carbonate reservoir rocks.

| Petrophysical | Geophysical | Aspect Ratio |
|---------------|-------------|--------------|
| Moldic (Vuggy) | Stiff       | 0.7-0.8      |
| Interstitial (Interparticle) | Reference | 0.12-0.15 |
| Microcracks    | Cracks      | 0.01-0.02    |

**Figure 1.** Geophysical pore-type classification in carbonates. A detailed description of the geophysical pore systems is as follows: a higher aspect ratio represents round stiff pores (vuggy or moldic pores), an intermediate aspect ratio represents reference pores (interparticle porosity) and a low aspect ratio indicates crack-like pores.

### 2. Rock Physics Model – Basic Theory, Data and Methodology

Pores type in carbonate rocks is very complex. They are classified based on their size, visibility and diagenetic and geometric complexity [2]. Despite that all these classifications are useful for characterizing petrophysical properties, relating these descriptions to a geophysical response is very challenging. This is because the seismic wavelength resolution is often much larger than the scale-size microstructure, so the wave can understand only the average effective properties of complex pore structures and not the individual pores and cracks [9].

Therefore, it can simplify the complex pore network into three geophysical pore types to reasonably represent the elastic properties response of carbonate reservoir rocks [10]. The geophysical pore types
are classified as (Figure 1): (1) Stiff pores with high-aspect ratios, which represent moldic and vuggy pores. (2) They consist largely of interparticle and inter-crystal pores and are considered as the dominant pore type in carbonates. (3) Cracks with lower aspect ratios, which represent micro-fractures and micro-cracks.

Our data is log data from carbonate reservoir rock. The type of hydrocarbon is gas. The data consist of log P-wave velocity, log gamma ray, log density, and log porosity. The visualization of the log data shown in Figure 2.

![Figure 2. Visualization of log data from carbonate reservoir rock.](image)

The rock physics modeling in carbonate reservoir rocks usually is obtained by the Differential Effective Medium (DEM) theory. Effective medium models have clearly featured to predict the approximate trends for the effects of porosity, pore shape, and mineral content on elastic properties. The DEM theory provides a tool to calculate the effective bulk and shear moduli for different pore types even when the volume concentrations are no longer small [7,8]. This scheme simulates porosity in a composite of two phases by incrementally adding a small number of pores (phase 2) into matrix (phase 1). The coupled system of ordinary differential equations can then be written as:

\[
(1 - \phi) \frac{d}{d\phi} [K^*(\phi)] = [K_2 - K^*] P^{(2)}(\phi) \\
(1 - \phi) \frac{d}{d\phi} [\mu^*(\phi)] = [\mu_2 - \mu^*] Q^{(2)}(\phi)
\]

(1)

with \( K^*(0) = K_1 \) the initial conditions and \( \mu^*(0) = \mu_1 \), where \( K_1 \) and \( \mu_1 \) are the matrix bulk and shear moduli respectively. \( K_2 \) and \( \mu_2 \) are the bulk and shear moduli of the inclusion phase respectively. \( \phi \) is the porosity and \( d\phi \) is the incremental change in porosity. \( P^{(2)}(\phi) \) and \( Q^{(2)}(\phi) \) are the geometrical factors depending on the aspect ratios (\( \alpha \)) of the elliptical pores [11].
In this research, we follow Xu and Payne’s extended Xu-White model for carbonates, in which the total pore space can be divided into three components: (i) stiff pores, (ii) reference pores and (iii) cracks [10]. The mix minerals present in the rock using Voigt-Reuss-Hill averages to obtain the elastic moduli of the solid rock matrix. The geometry-related pores with bound water are added first and will be included in the solid material for fluid substitution and then three geophysical pore types are added using the DEM scheme to obtain the dry effective bulk and shear moduli. The illustration of detailed rock physics modeling steps is given in Figure 3.

3. Result and Discussion
The elastic modulus value of $K_{\text{min}}$, $\mu_{\text{min}}$, $\rho_{\text{min}}$ initials was obtained from the reservoir characteristic of petrophysics data with reference value: $K_{\text{calcite}} = 76.8$ Gpa, $\mu_{\text{calcite}} = 32$ Gpa, $\rho_{\text{calcite}} = 2.71$ g/cm$^3$, $K_{\text{illite}} = 62.2$ Gpa, $\mu_{\text{illite}} = 25.7$ Gpa, $\rho_{\text{illite}} = 2.71$ gr/cm$^3$, and $K_{\text{gas}} = 0.038$Gpa. Figure 4(a) shows the distribution of cross-plot data between porosity and P-wave velocity. The majority of the data is within the Voight and Reuss bound line. From the distribution of the data above, it is seen that the type of mineral-filled in the formation is the same, although there is some data outside the curve Voight and Reuss bound. This indicates the presence of other minerals besides calcite and clay (illite) in the carbonate reservoir in the study area.

![Figure 3. The illustration of detailed steps of rock physics modeling in carbonates reservoir rocks (Modified from [10]).](image1)

![Figure 4. (a) The cross-plot of Voight and Reuss bound and the color scale shows the value of gamma-ray index. The presence of other minerals besides calcite and clay (illite) in the carbonate reservoir in the study area. (b) The cross-plot of DEM theory line to predict the pore geometry of carbonate rock. The data dominant in the interval of reference pore type to cracks-micro-cracks. The value of aspect ratio between 0.05 – 0.1 respectively.](image2)
Figure 4(b) shows the results of pore geometry modelling using the DEM Model. The value of $\alpha_{ref} = 0.05$, $\alpha_{crack} = 0.01$, $\alpha_{stiff\ pore} = 0.1$. So that, the distribution of $\alpha$ obtained from cross-plot between porosity and $V_p$ determine that the pore geometry of the three wells has a high similarity with the majority of interparticle and micro-cracks. Moreover, pore geometry interprets the effects of seismic wave velocity towards carbonate reservoir of the study area, stiff pores or the increasing of $\alpha$ values will make the seismic wave velocity to increase rapidly and crack pores or the decreasing of $\alpha$ values will make the seismic wave velocity slower. The results of the local pore geometry modeling study indicate that the reservoirs are pretty well-qualified because the interparticle and micro-cracks pore permeability reservoirs can drastically increase and interpret the sweet spots of permeability carbonate reservoirs [2].

By using the forward modelling on DEM theory, we can get the $V_p$ and $V_s$ prediction value of DEM model, but this research is focusing more on the comparison of $V_p$ and $V_s$ because in there only log $V_p$ value is available. Figure 5 shows the results of plotting $V_p$ measurement and $V_p$ prediction on the depth with different $\alpha$ values at each depth. From the Figure 5, we return the process to obtain the best fit of velocity data and velocity prediction by controlling the value of aspect ratio. It is resulting in decreasing value of aspect ratio by the increasing value of depth. It possible because of the implication of the overburden in the reservoir rock.

![Image](image_url)

**Figure 5.** The cross-plot of velocity data and velocity prediction of carbonate rock. The value of aspect ratio indicated the geological process that the study area is controlled by overburden geological process.

Generally, we have done work in the common geological condition in carbonate reservoir rock. The value of aspect ratio indicated the fracturing is closely related to overburden and differential compaction, thus increasing the connection between separate vugs and enhancing permeability dramatically.

4. **Conclusion Remark**

Pore-type geometries in carbonate field control the fluid flow properties and also by geological history, but the complexity of pore geometry/structure would be suitable prediction of pore-type distribution from geophysical measurements. In this research, we have demonstrated that three geophysical pore types (stiff pores, reference pores and cracks) work effectively in quantifying the effects of pore type on the elastic properties of carbonates reservoir. This study also shows that the proposed rock physics model by using DEM theory assess a good quantitative characterization of pore-type from well log data. Following the real data and combination of rock physics modeling, our reservoir has a dominant crack/micro-cracks pore type that indicates the geological process which is controlled by overburden and differential compaction.
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