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Standardization of Rock Physics Parameter for Carbonate Characterization

Abstract

Realistic estimation of pore type and its distribution is extremely important for effective carbonate reservoir characterization, as it has direct effects on the velocity, impedance and others rock physical parameters. Moreover, the fluid distribution and thereby the productivity is directly dependent on the pore type.

This paper emphasized the results of a series of numerical simulations that have been carried out by changing composition, pore type and saturation. Effective elastic moduli of the system has been calculated using stepwise application of Differential Effective Medium (DEM) Theory. Different scenarios as conceived in simulation revealed complex response of Vp, Vs, P-Impedance, S-Impedance, Poisson's ratio, Vp/Vs ratio etc. with change of pore aspect ratio, porosity and saturation. It is found that Poisson's ratio is a good indicator of pore typing.

Standard templates have been prepared which can be integrated with DSI, Sonic Scanner log observations to determine the pore types and ultimately fluid distribution.

Introduction

Difference between carbonates and clastic reservoirs arise due to variedly different depositional environments, process, and complex diagenetic history that the carbonates undergo (Anselmetti and Eberli, 1993; Lucia, 1995). Carbonates are chemically metastable and due to variation in water depth, burial depth, temperature and pressure, carbonate rocks undergo intense cementation, dissolution and dolomitization (Brie, Johnson and Nurmi 1985). Presence of varied types of porosity, such as interparticle, intraframe, mouldic, vuggy and microcracks or fractures in carbonate are the consequence of intense diagenetic alteration that completely obliterates mineralogy and texture of the original framework. Prime hurdle of quantitative carbonate reservoir characterization is bipartite. The first one, being distinguishing the reservoir facies from tight/non reservoir facies followed by fluid type determination.

Producibility in carbonate is strongly related to the complex pore structures (Anselmetti and Eberli, 1993; Lucia 1995). Presence of varied types of pore structures in carbonates make the porosity partitioning a very complex process to accomplish. Moreover, modified response of rock physics parameters due to diagenetic effects and presence of different clay minerals within pores escalate the complexity to a greater degree. High degree of scattering in porosity-velocity relationship occurs due to presence of complex pore systems. Generally, carbonate rocks exhibit very good cementation and grain contact elasticity is not an important factor determining elastic properties (Han 2004). Therefore the scatter in the porosity-velocity relationship for a given mineral composition and fluid type is due to pore type effect (Sayers 2008).

In this paper, using Differential Effective Medium (DEM) theory, a series of numerical simulations have been carried out by changing carbonate composition, pore type and fluid saturation. Parameters like P-Impedance, S-Impedance, Poisson's Ratio, Vp/Vs Ratio have been catalogued to understand the various pore type effects and fluid responses on seismic and log signatures.

Theory

Differential Effective Medium (DEM) theory is the process of modelling multiphase composites by incrementally adding inclusions of one phase in sequential manner to the matrix phase (Norris, 1985). At initial stage phase 1 (maximum concentration phase) is considered to be the matrix while the concentration of phase 2 is considered to be zero. Step wise concentration of each phase is changed as a new increment of phase 2 material is added. The process is continued until the desired proportion of the constituents is reached. Effective moduli of the medium depend on the construction path taken to reach the final composite. For multiple inclusion, shapes or multiple constituents, the effective moduli depend not only on the final volume fractions of the constituents but also on the order in which the incremental additions are made. The process of incrementally adding inclusions to the matrix is a thought experiment and must not be considered to be an accurate description of the true evolution of rock porosity in nature.

The coupled system of ordinary differential equations for the effective bulk and shear moduli, K* and μ*, respectively, are (Berryman, 1992)

$$(1-y)\frac{d}{dy}[K^*(y)] = (K_2 - K^*)P^{(*2)}(y)$$

$$(1-y)\frac{d}{dy}[\mu^*(y)] = (\mu_2 - \mu^*)Q^{(*2)}(y)$$

At initial conditions K*(0)= K1 and μ*(0)= μ1, where K1 and μ1 are the bulk and shear moduli of the host material (phase 1), K2 and μ2 are the bulk and shear moduli of the incrementally added inclusions (phase 2), and y is the concentration of phase 2. For fluid inclusions and voids, y equals the porosity (φ). The terms P and Q are geometric factors.

Methodology

For the calculation of Effective moduli, DEM theory was applied in stepwise manner. Xu-Payne multi step approach (Xu and Payne, 2009) has been modified to incorporate different pore shapes and fluid mixture response to model bulk and shear modulus of saturated media and in turn to predict different porosity proportion. Detailed procedural implementation is explained step by step below.

1. Preparation of solid rock matrix by mixing of different compositions present in the rock using Voigt-Reuss-Hill (VRH) average method (Hill, 1952) by considering individual constituent mineral's experimentally derived bulk and shear modulus.
2. Infusion of water wet clay related micropores in to the solid matrix and calculation of effective elastic parameters using DEM theory
3. Introduction of various pore types e.g. moldic/intraframe/vuggy, hereby called vuggy pore, intergranular/ intercrystalline /interframe, with certain percentage in to the system to form "dry" rock frame and calculation of effective elastic parameter applying DEM theory.
4. Calculation of effective bulk modulus of mixed fluid using Wood's Suspension Model (Wood, 1955).
5. Fluid mixtures have been added to the dry rock frame and effective elastic moduli of saturated rock has been calculated using Gassmann's Equation (Gassmann, 1951; Biot, 1956)
6. Calculation of bulk density of the saturated medium.
7. Calculation of Vp, Vs, Poisson's Ratio, P-Impedance, S-Impedance, Vp/Vs from the effective elastic moduli.

To implement the algorithm, an executable code has been written on Python 2.2 environment. This program uses NumPy library for matrix manipulation.

Applying the methodology, elastic properties have been simulated for various scenarios by changing the composition. Elastic properties were simulated for various scenarios by changing composition using above methodology. Details of compositional changes in each scenario are given in Table-1.

Scenario	Calcite	Dolomite	Vclay
I	100%	0	0
II	90%	10%	0
III	80%	20%	0
IV	70%	30%	0
V	90%	0%	10%
VI	80%	0%	20%
VII	70%	0%	30%

Table-1: Simulation scenarios considered for elastic property generation

In each simulation scenario parameters, are calculated for 60%, 40% and 20% oil and gas saturation, different pore types i.e. vug, reference and fracture and in 0-40% porosity range . In this study, illite is considered only clay, but clay mixture also can be accommodated. Dry gas and black oil is considered as pore fluid and their bulk moduli is generated using standard correlations. Various input parameters like aspect ratio of pores, bulk and shear modulus of matrix materials, fluids, densities etc are placed in Table 2.

Bulk Modulus	Calcite- 77 Gpa Dolomite- 95 Gpa Illite – 60.1 Gpa Water – 2.2 Gpa
Shear Modulus	Calcite- 32 Gpa Dolomite- 45 Gpa Illite – 25.3 Gpa Water – 0 Gpa
Density	Calcite- 2.71 gm/cc Dolomite- 2.83 gm/cc Illite – 2.6 gm/cc Water – 1.0 gm/cc Oil- 0.8 gm/cc Gas – 0.05 gm/cc
Pore Aspect Ratio	Vug- 0.8 Reference Pore – 0.15 Fracture- 0.01 Clay Pore – 0.01

Table-2: Input parameters for simulation scenarios considered for elastic property generation

Results and Discussion

As discussed, the effect of pore type on the velocity (Vp and Vs) is most important factor in Rock Physics modelling. Both Vp and Vs steadily decrease as aspect ratio of the pore decreases. Figure 1 depicts the relationship between Vp and Vs with aspect ratio in 100% calcite that is fully saturated with water.

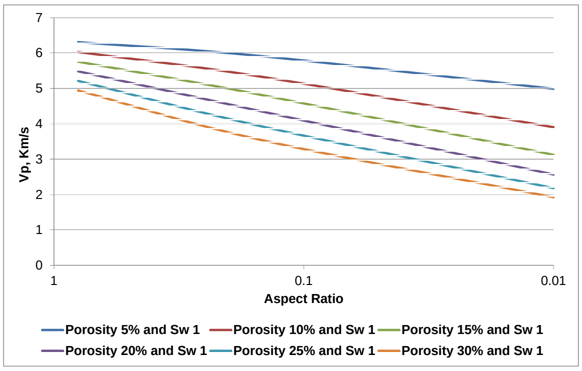

Figure 1a: Change of Vp with respect to pore aspect ratio

Most of the times moldic, intraframe and vuggy pores have the tendency to be rounded, while sphericity decreases considerably in interparticle, interframe, micro cracks and fractures.

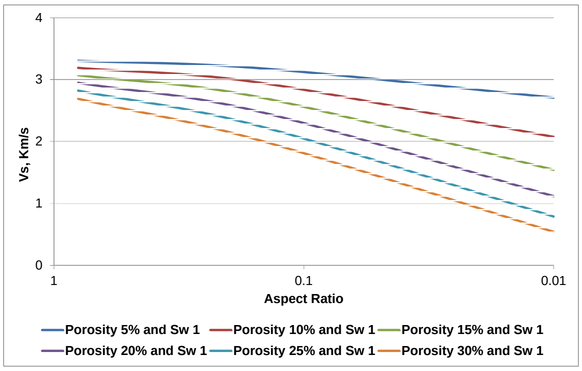

Figure 1b: Change of Vs with respect to pore aspect ratio

High abundance of these spherical pores makes the rock stronger. Both P and S-wave travel faster in the rocks having high percentage of spherical pores compared to the rocks having abundance on elliptical pores. Spherical pores are very resistant to stress due to roundness and called compliant pores. While the elliptical pores are less resistant to stress, susceptible to change in volume and shape. Higher abundance of these pores makes the rock weaker. These pores are called non-compliant pores.

It is evident from the Figure 1 at higher porosity Vs decrease faster with respect to aspect ratio than Vp. This indicates highly nonlinear behavior of Vp/Vs with aspect ratio (Figure 2). Lowering of aspect ratio increases the Vp/Vs drastically. Vuggy and reference pores show negligible change of Vp/Vs and values vary between 1.90 and 1.75 in case of 100% calcite saturated fully with water. In case of fractures Vp/Vs varies between 1.85 and 3.55.

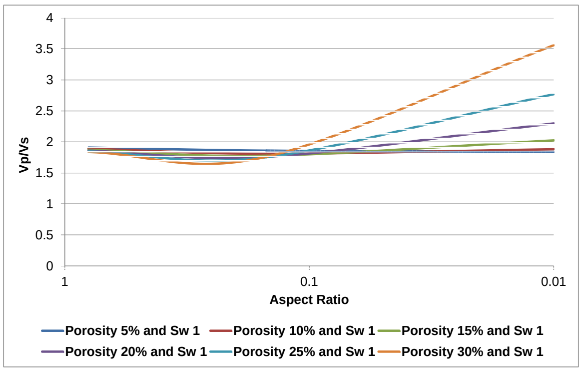

Figure 2: Change of Vp/Vs with respect to pore aspect ratio

On the other hand, Poisson's ratio shows reasonable good separation in case of vuggy and reference pores and in factures also (Figure 3). In case of fracture system it ranges between 0.29 to 0.45 and for vuggy and reference pore system it varies between 0.26 and 0.31 in 100% calcite fully saturated with water.

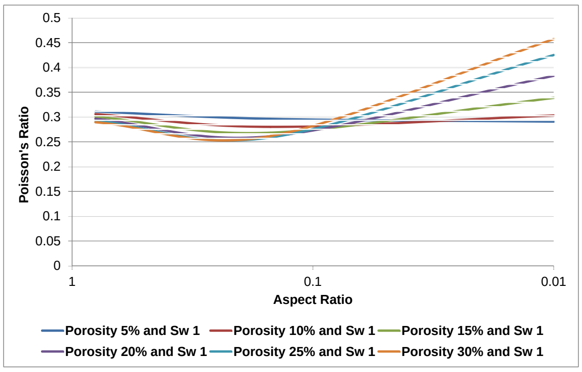

Figure 3: Relationship between poisson's ratio and pore aspect ratio in 100% water saturation

Therefore, for a rock with known composition and saturation, identification of pore type is possible with the help of Poisson's ratio and Vp/Vs values. Increasing the saturation of oil and gas lowers the velocity (both Vp and Vs) as a whole and separation in VP/Vs and Poisson's ratio domain increases. Figure 4a depicts the change of Poisson's ratio with aspect ratio in 100% calcite rock 50% saturated with dry gas and Figure 4b describes the same relationship in 100% calcite rock 50% saturated with black oil.

P-Impedance vs total porosity relationship clearly distinguished the different pore types. Varied oil and gas saturation curves only followed the envelop formed by 100% water saturated rock. Therefore it reveals that if pore type and composition is known then by this plot hydrocarbon type can be determined. Figure 5, 6, 7, 8, 9, 10 and 11 represent P-Impedance vs total porosity for all the considered scenarios.

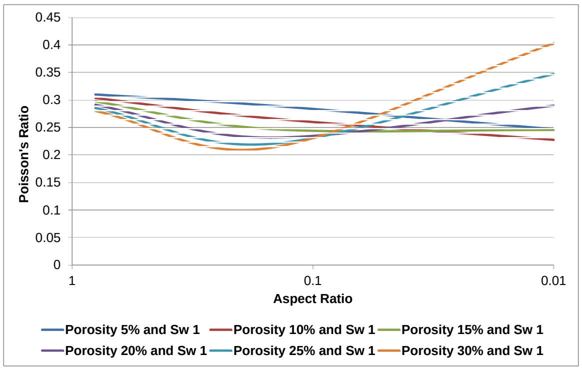

Figure 4a: Relationship between poisson's ratio and pore aspect ratio in 50% gas saturation

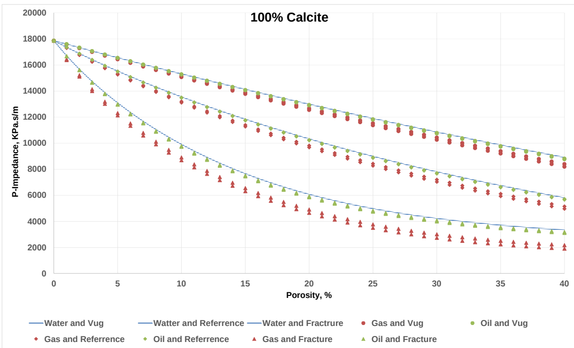

Figure 5: P-Impedance vs total porosity relationship for 100% calcite

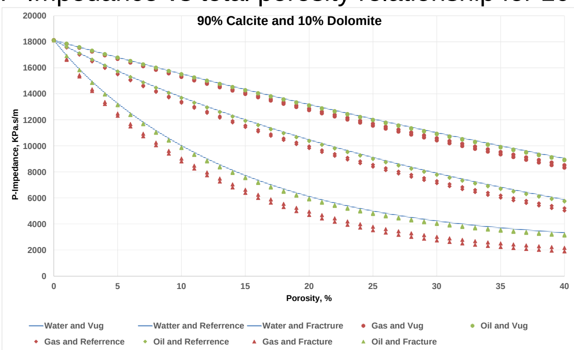

Figure 6: P-Impedance vs total porosity relationship for 90% calcite and 10% dolomite

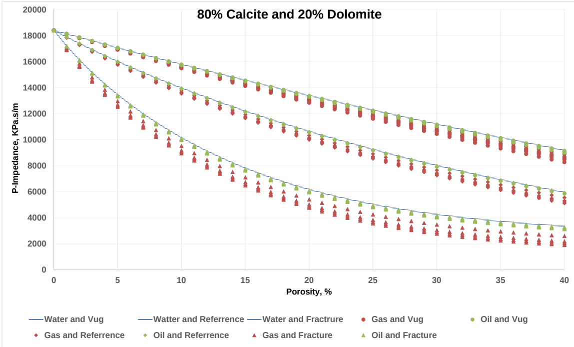

Figure 7: P-Impedance vs total porosity relationship for 80% calcite and 20% dolomite

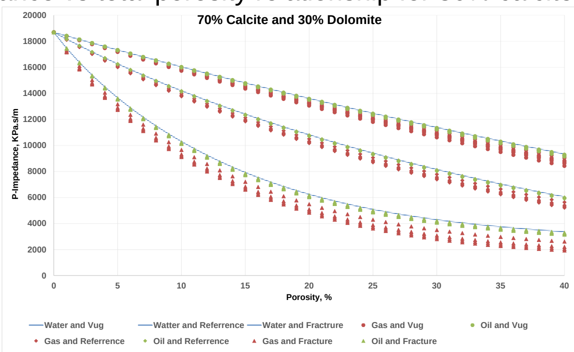

Figure 8: P-Impedance vs total porosity relationship for 70% calcite and 30% dolomite

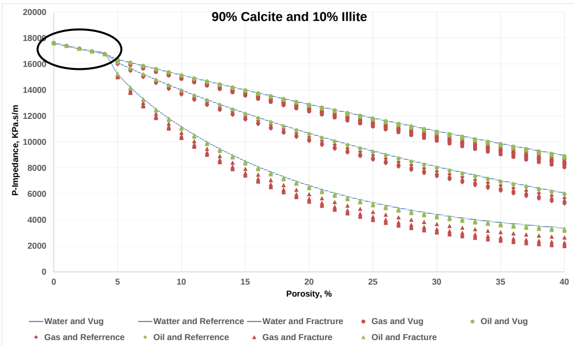

Figure 9: P-Impedance vs total porosity relationship for 90% calcite and 10% illite

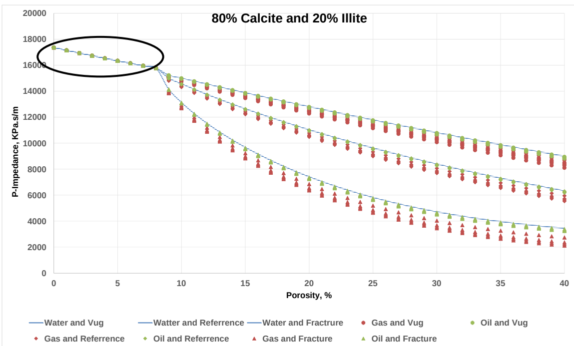

Figure 10: P-Impedance vs total porosity relationship for 80% calcite and 20% illite

All the scenarios generated in this study reveal that dolomitization increases the velocity and in turn increases the P-Impedance. Therefore progressive dolomitization has pulled up the whole system of curves to the higher P-Impedance level.

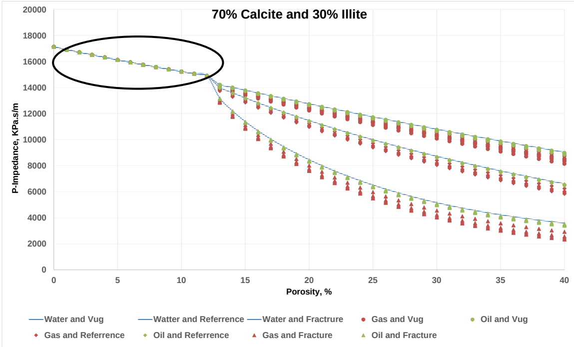

Figure 11: P-Impedance vs total porosity relationship for 70% calcite and 30% illite

Effect of illite (clay) has negative impact and it decreases the overall P-Impedance but the whole family of curves maintains the shape.

In the figure 9, 10 and 11 at low porosity section a flat spot is observed. It is due to the fact that illite being clay it is introduced into the system prior to main pore system, while performing the DEM calculations. As stated earlier DEM is a thought process not actual rock forming sequence, since clay related micropores have been infused into the matrix system prior to main pore system and all the clay pore are water wet therefore at low porosity portion of the plot 100% water saturation have been shown.

Vp/Vs ratio and Poisson's ratio posed very complex relationship with porosity (Figure 12 and 13) and determination of fluid characteristics vis-à-vis pore type directly from these curves is somewhat tricky.

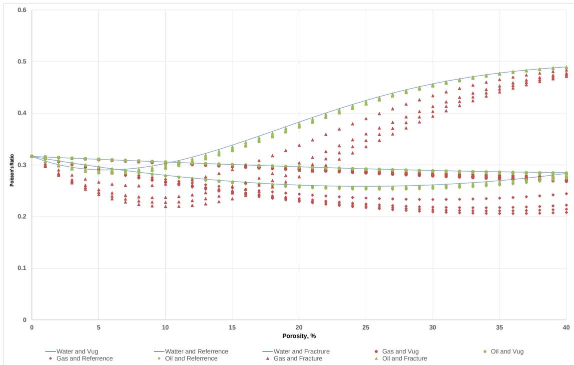

Figure 12: Poisson's Ratio vs Porosity relationship for 100% calcite rock

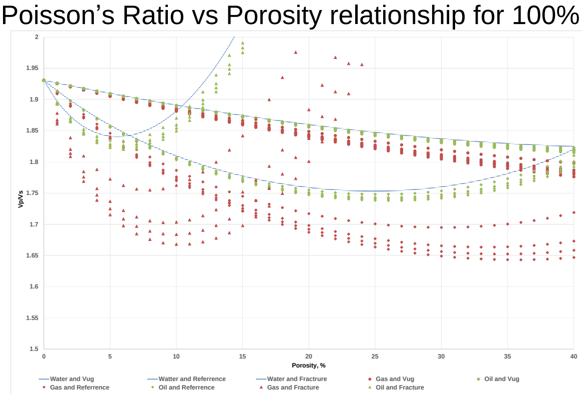

Figure 13: Vp/Vs Ratio vs Porosity relationship for 100% calcite rock

Field Application

This methodology applied in the Miocene carbonate reservoir of NBP field. In NBP field oil accumulation in carbonate reservoirs is in three pay levels viz, Upper, Middle and Lower. Well NBP-X2 is situated in the middle part of the field and drilled through Middle and Upper pay. DSI logs were recorded in this well in Middle pay section. Using the Poisson's ratio derived from the DSI logs and use of standard templates classified the dominant pore type to be reference with occasional patchyvuggy pores in Middle pay section (Figure 14).

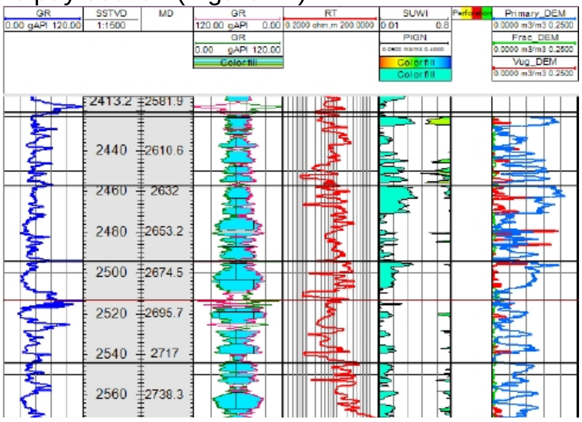

Figure 14: Pore type classification carried out in well NBP-X2

Conclusions

- Differential Effective Medium (DEM) theory has been applied in step wise manner to calculate effective moduli of the system. Executable code in Python environment has been specially designed for this purpose.

- Responses of Vp, Vs, P-Impedance, S-Impedance, Poisson's ratio, Vp/Vs ratio etc. with pore aspect ratio, porosity and saturation are very complex. Analysis of the responses revealed that Poisson's ratio is an important factor for pore type determination. Poisson's ratio-aspect ratio template specifically designed in this study for water saturated zone helps to determine the pore type of carbonate rock system.

- Readings of Shear sonic and DSI logs coupled, with the newly developed template in this study can be utilized to classify the pore types.

- Once the pore type determination is complete P-Impedance- porosity templates can be utilized further to prepare fluid profile calibrate the pore types.

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