Characterization of Heterogeneities in Carbonates

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Summary

Heterogeneity in carbonate rock is the principal reason for its improper characterization and this becomes more apparent as attempts are made to characterize petrophysical properties at various scales. Dissolution, precipitation, and cementation effects commonly found in carbonates can change the basic framework and strength of carbonate rocks making them more heterogeneous and thereby affecting seismic properties. These properties are important to understand should be accounted for obtaining elastic properties of these carbonate rocks. Similar to velocity, permeability is a complex measure of the heterogeneities and anisotropy present in the rock. Some of the available forward rock-physics models do consider the anisotropy but all models lack to account for the heterogeneity in the rocks. We examine here various laboratory methods to understand and map carbonate rocks. We believe that a correlation among these features will help in characterizing the nature of heterogeneity in the rock and will provide a control on reliable analysis of the results/output values.

Introduction

In the present study, we conducted a series of lab experiments on carbonate cores and logs to understand and quantify the observed changes in velocity, modulus, poisson's ratio between the dry and the saturated states and tried to relate it to the amount of heterogeneity present in the rock. Permeability is another important factor controlled by collective action of rock and fluid interactions in association with accompanying pressure and temperatures. The uncertainty in permeability is necessary to be addressed for better optimization of production strategies and to maximize recovery of the bypassed oil.

Previously scientists have discussed in specific the importance of pores and fluids in terms of the effects it can create on the measured elastic properties. Different schools of thought exist on this subject. Many believe that porosity is the most important factor controlling sonic velocity, and that pore-fluid type has no statistically relevant influence (Rafavich *et al.*, 1984 & Wilkens *et al.*, 1984). But various studies show that pore type, pore fluid compressibility, and variations in shear modulus due to saturation are also important factors for velocities in carbonate rocks. Some studies have reported a reduction of shear modulus due to saturation in low porosity chalks, and oolitic grain- and packstones (Japsen *et al.*, 2000 & Assefa *et al.*, 2003). In the first of its kind work on carbonates combining the ultrasonic (0.8 MHz) and seismic (3-3000 Hz) frequency range, Adam *et al.* (2006) extensively studied the change in moduli as a function of porosity and fluid saturation. We have also found that, upon saturation, the shear strength of the rock no longer remains the same, varying with the kind and amount of saturation, and with the ambient environments. This analysis is crucial in any attempt to explain why different parts of a single formation, in close proximity to one another, behave differently in terms of holding and transporting hydrocarbons.

Data Types and Analysis

Sample Description

Aligned to the borehole axis, a vertical 1.5" diameter carbonate rock samples from the same formation spread over three wells (not far from each other) are used in the present study. Results from ESEM, EDAX, acid-residual test and well logs were used to ascertain the mineralogies (carbonate, clay and quartz) variations in the samples. Physical inspection and the preliminary investigations suggest that the limestone is highly heterogeneous with selective, but varying degrees of dissolution creating fair to good secondary porosity in the form of solution vugs, molds and channels (Figure 1).

CT Scan

The computed tomography (CT) scan provides evidence of fractures, vugs, and heterogeneities as indicated by the magnitude of the variation in CT density (Figure 1). CT can be used for qualitative and quantitative analysis of internal features, if those features have sufficient differences in atomic composition or density or both. However we may have lithology changes or micro cracks below the CT resolution in size as well as in contrast. Quantification of such heterogeneities is challenging but necessary for proper characterization of the rock. We propose an approach to quantify the heterogeneity of the core sample (equation 1) on the basis of the available CT density values to compare it with the variation in velocity values across the region of heterogeneity. We use only those CT numbers contributing more than 5%to the bin concentration.

$$Heterogeneity\ Number(\%) = 0.5 * \frac{Maximum\,CT\ \ Number(>5\%) - Minimum\,CT\ \ Number(>5\%)}{CT\ \ Number\ Highest\ Bin\ Percentage}\ x100$$

Acid Residual Tests

Table 1 shows data pertaining to the residual analysis. We used varying concentrations of Hydrochloric Acid (HCl) to dissolve calcium carbonate in the core sample. The residual amount is considered as clastic component. This method gives an approximate amount of calcite in the sample.

However, in order to calculate the effective modulus of the dry rock, we must calculate or derive percentage by volume of the other minerals that remain present in the rock. These weight were then used for forward model (VRH average) the bulk density and porosity of the rock and were compared with results from other experimental methods (Beckman Pycnometer, Archmidies principle, CMS-300, AP-608)

Permeability Measurement

Point permeability on the samples were measured using a Pressure Decay Profile Permeameter (PDPK-200) that uses nitrogen gas and measures permeabilities reliably from 0.001 mD to 30,000 mD. Although the PDPK effectively measures the permeability only up to an inch into the sample, it still could show the variation in the permeability values across the surface indicating anisotropy in the sample. Similar to the velocity anisotropy this is also attributed to the heterogeneity in the sample. Permeability was also measured under pressure using CMS-300.

Saturation Effects

The calcite and dolomite present in matrix and cement may get dissolved in the pore fluids. This process may open new permeability channels in the rock, or alternatively, may block old channels through precipitation. To look at the exact saturation effects, the core samples should be saturated under the reservoir pressure and temperature. In the present study we saturated the cores under vacuum (–27 mm of HG) with no external pressure and again at 1000 psi with NaCl as saturant (8000 ppm) in both the cases and achieved partial (about 50%) and full saturation respectively. The calcite rich matrix absorbed more than twice as much fluid under this higher pressure.

Ultrasonic Measurements

Ultrasonic measurements on the core samples in dry, partial and full saturation conditions were carried out using a 1MHz pulse (Figure 1). The waveforms collected for different samples were very indicative of the internal morphology of the sample. The travel time measured is converted into velocity of the wave in the core sample of known length. The velocities were then used to calculate the elastic properties of the rock. As the method is empirical, the values are only representative and not actual.

Scanning Acoustic Microscope (SAM)

This technique uses an acoustic beam of known high frequency (50 MHz in this case) and maps the impedance contrast in the sample. Cross-section and depth profiles can be created for surface and body scan at any point and depth in the sample for any mapped impedance contrast. The mapped impedance boundaries are then used for making velocity measurements across the sample to find the velocity variation and compare it with the amount of heterogeneity as calculated using CT scan images.

Results and Discussions

Images from ESEM confirm the presence calcite along with clay and quartz minerals. Table 1 shows data pertaining to the residual analysis. The available CT scan images along with the density numbers are displayed in Figure 1 for sample D (heterogeneous) and sample J (homogeneous). These density numbers were used to calculate the heterogeneity number or the percentage of heterogeneity in the sample using equation 1. The samples used in this study were found to be 43% (DV) and 17% (JV) heterogeneous. From the wave form displayed in Figure 1, it can be seen that the heterogeneous sample (DV) is more anisotropic than homogeneous sample (JV). No significant layers were imaged in SAM. We believe that this waveform variation is due to the heterogeneity present in the rock. This heterogeneity could be due to the pore types and their orientation in the sample. The permeability experiment under pressure revealed that most of the pores are compliant. Under pressure the sample porosity and permeability reduces significantly suggesting that these pores are low aspect ratio pores like fractures and cracks as is also indicated by the CT scan images. Porosity from PDPK measurements varied from 18% to 30%, whereas permeability ranged from 0.18 mD to 80 mD. Porosity and permeability measured using CMS-300 varied from 17% to 19% and from 1.5 mD to 29 mD respectively. However, the two sets of values are not in good correlation with each other. The reason is presence of compliant pores and their participation in flow of fluid depending on their alignment under pressure. In order to map the regions of heterogeneity inside the sample we analyzed the core sample under acoustic microscope. Using the surface scan and body scan of the samples we can make out that there is region of strong impedance contrast in the heterogeneous sample. To map the related velocity heterogeneity in the sample, benchtop velocity measurements for both compressional and shear (S1 and S2) waves were carried out at ultrasonic frequencies at 5 equidistant points on the circular arc. The velocity variation for sample DV and JV are shown in Figure 1. Table 1-3 contains data from the saturation effects of fluid on carbonates for both partial and full saturation case. Samples show variation in shear strength after saturation that comes back to the original level in some cases after the saturants are removed. This is an important factor to be considered while designing realistic models for reservoir simulation. The P-wave velocity shows variation of up to +5% and +15% for sample DV and JV respectively. Also important to note is that the magnitude of variation in velocity at partial saturation is in no correlation with variations at full saturation. As for sample JV, at partial saturation the P-wave shows a variation of -6%. In both these cases, the variations are more than what can be accounted for change in density of the saturated sample.

The effects of saturation are more pronounced for the shear wave velocity. For sample DV, shear velocity recorded a decrease of up to -8% for the fully saturated case, whereas sample JV recorded a decrease of -22% and -13% for partially and fully saturated conditions respectively. Again these changes in velocities are more that what can be accounted for the change in density of saturated sample. The analysis of the change in physical properties of the rock after interaction with fluids suggest that carbonate rock matrix upon saturation (specifically with water based fluid), can react with the saturating fluids and can alter the physical and petrophysical properties. These changes in the rock matrix affect subsequent observations, which are based on the elastic properties of the rock matrix. The amount of alteration is a major function of the types of fluid with which the rock has been saturated. In some instances, it may also be a function of the length of time during which the fluid remained in contact with the rock. The normalized plotting of velocity and permeability values does not indicate any strong correlation for areas of changed morphology. However, the most consistent observation is that all the plots in Figure 9 show the second dry cycle case. The average permeability of all classes is around 11 mD. Values range from 0.18 mD to 80 mD. Strongly heterogeneous samples have high permeability. Less heterogeneous samples have intermediate permeabilities. The most homogeneous sample (J) has the lowest permeability. Vertical plugs have a more extreme permeability range than do horizontal plugs. A similar trend is also seen in the velocity values.

Hence, permeabilities anisotropy has a correlation with velocity anisotropy. However, Figure 9 shows that there is no obvious, generally applicable correlation between velocity and permeability.

Conclusions

Effects of saturation in heterogeneous carbonate are governed by many factors, including mineralogy, pore types, pore alignment, etc. Partial saturation at ambient condition or higher pressures, are much more important in terms of the effects on velocity because of the influence of saturation. There is no correlation between point permeability values to measured velocity values. We need to more thoroughly explore the relation between heterogeneities and other transport properties of rocks

Although characterization of heterogeneities at the lab scale is only a starting step and the approach can be quantified by making the suggested observation and measurements on samples considered in close approximation of the reservoir character.

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Table1. Measured Properties

Sample	Carbonate (%)	Clay (%)	Quartz (%)	GD (g/cc, VRH)	Porosity (MM, %)	Porosity (%, PS)	Porosity (%, FS)	Porosity (AP, %)	Perm (mD, PDPK)	Perm (mD, CMS-300)
DV	0.45	0.32	0.23	2.66	28.2	12.58	22.72	23	25.31	
KV	0.45	0.36	0.19	2.66	29.1	14.93	26.34	27	7.59	2.72
JV	0.53	0.4	0.07	2.66	19.8	19.29	19.73	20	10.99	15.163

MM- Mineralogical Model, AP- Archimedes Prin., FS-Full Saturation, PS- Partial Saturation, PDPK- Pressure Decay Profile Permeameter, VRH-Voigt-Reuss-Hill

Table 2. Elastic Properties at Partial Saturation

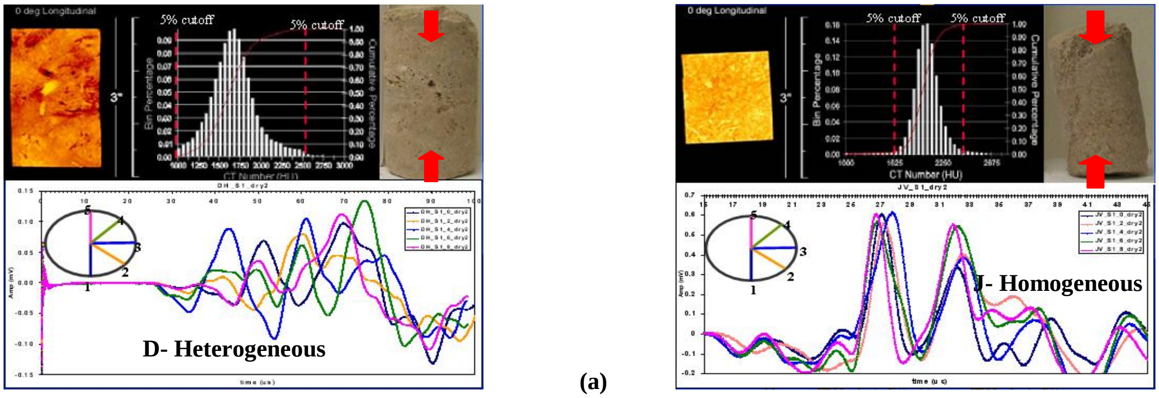
Sample	Vp at PS (m/s)	Vs at PS (m/s)	K at PS (GPa)	μ at PS (GPa)
DV	3750	2040	22	10.5
KV	3100	1750	14	7.3
JV	3050	1550	14.5	5.6

Vp- Compressional Velocity, Vs- Shear Velocity, PS- Partial Saturation, FS- Full Saturation

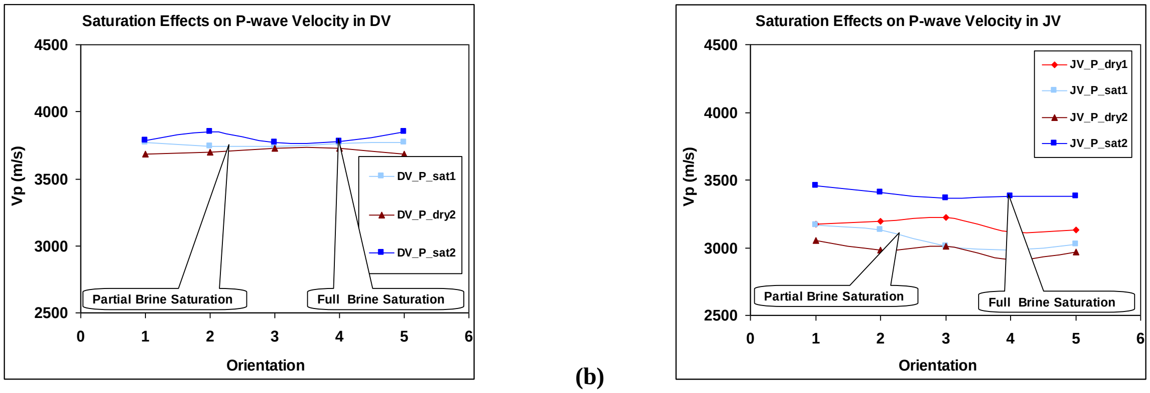
Table 3. Elastic Properties at Full Saturation

Sample	Vp at FS (m/s)	Vs at FS (m/s)	K at FS (GPa)	μ at FS (GPa)
DV	3820	2000	23.5	11
KV	3200	1600	18	6.6
JV	3390	1590	21.2	6.9

PS- Partial Saturation, FS- Full Saturation, K- Bulk Modulus, μ− Shear Modulus



(a)



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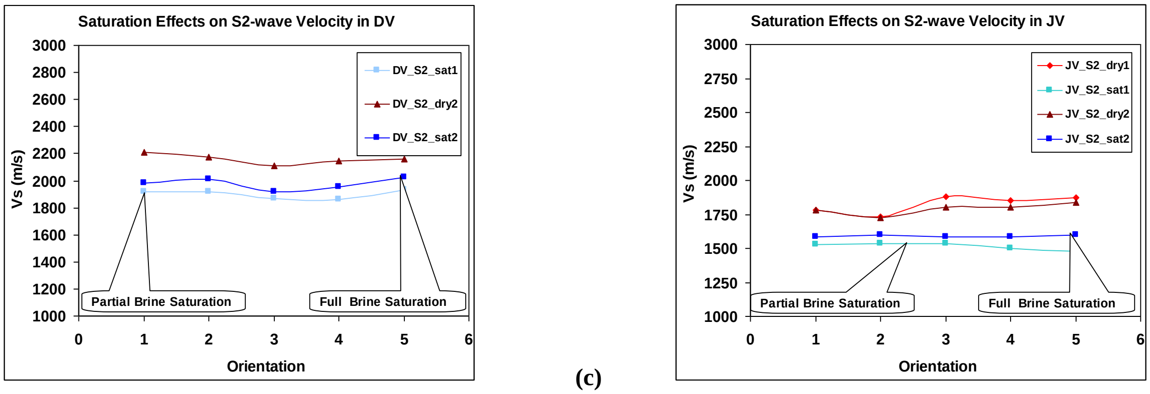

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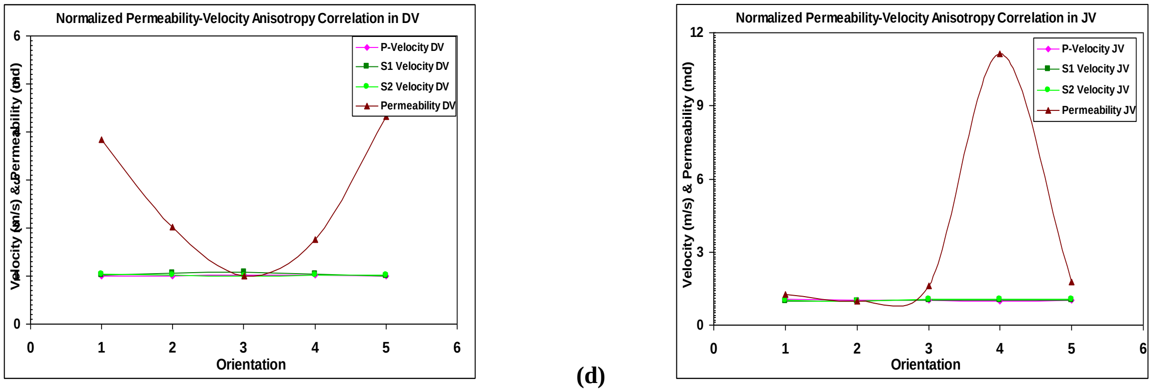

(d)

Figure 1. Results for sample DV (left) and sample JV (right) showing CT scans and seismic waveform (a); effects of saturation on Vp (b) and Vs (c); and the correlation between permeability and velocity anisotropy (d).

EDITED REFERENCES

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