



**P-292**

## **Elastic Properties of Carbonate: Effects of Fluids Frequency And Heterogeneity**

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### **Summary**

*Elastic properties often derived by inverting seismic and well-log data, form important input for reservoir engineering calculations and simulation studies. Often in absence of site-specific measurements at reservoir temperature and pressure, empirical models or data from analog formations are used. However, elastic properties of rocks are controlled by variation in saturant type, effects of pressure and temperature, in addition to rock heterogeneity. This paper discusses the effects of fluids, frequency and heterogeneity on the elastic properties of carbonate rocks.*

*In this study, comparisons are drawn between homogeneous and heterogeneous samples for their varied response to varying saturant, amount of saturation ( $S_w$ ), frequencies and differential pressures. At ultrasonic frequencies, we observe that most samples show an increase in bulk modulus upon saturation. However, consistent weakening is observed for shear modulus in all samples. The analysis shows that in reservoirs with patchy distribution of homogeneous and heterogeneous facies, one has to deal with 22% to 45% variation in bulk modulus and around 17% to 10% variation shear modulus in going from partial to full saturation respectively. Also discussed is that fact that the amount of saturant and state of saturation in such formations under varying heterogeneities are very crucial for estimating the amount of bypassed oil in a particular setting type.*

### **Introduction**

Heterogeneity in lithology and saturation (uniform versus patchy), and the saturants themselves are known to affect the measured elastic and flow properties in carbonate rocks (Adam et al., 2006). Rafavich et al. (1984) and Wilkens et al. (1984) suggest that porosity is the most important factor controlling velocity, and that pore-fluid type has no statistical relevance. However, Japsen et al. (2000) and Assefa et al. (2003) have shown that pore type, pore fluid compressibility, and saturation affect velocities and elastic moduli in carbonate rocks. Adam et al. (2006) in their experiments on carbonate rocks at ultrasonic (0.8 MHz) to seismic (3-3000 Hz) frequencies, document changes in shear modulus as functions of porosity and fluid saturation. The frequency at which laboratory data is measured is another important factor that requires careful upscaling for proper implementation of laboratory results to the field. Winkler et al. (1982) suggested that even at a very low strain amplitude (seismic and sub seismic frequencies), pore fluids can have a strong effect on attenuation in saturated rocks as compared to their dry state. The above

reasons call for proper characterization of heterogeneities to obtain correct estimates of elastic and flow parameters in the reservoir. Extra efforts are required to make sure that these values remain consistent and constrained even at upscaled (geological models for reservoir simulations) calculations and reliable for field implementation.

We investigated the difference in measured elastic properties of homogeneous (J) and heterogeneous (D) carbonate samples in response to fluid saturation. We also analyzed the effects of varying saturants, frequency, and differential pressure on the elastic properties of different set of carbonate rocks. The greater picture for the application of this study is to develop realistic geological models for input to a simulation model with adequate representation of the variations in lithology, petrophysical properties and other flow related heterogeneities in the reservoir.

### **Data Used**

One set of measured data and one set of literature data is analyzed in this paper.



#### a) Measured Data

Carbonate samples from the same formation spread over three near by wells are used. The samples were cored vertical with respect to the borehole axis. CT scans, ESEM (Scanning Electronic Microscope), XRD (X-ray Diffraction), acid-residual tests and well logs are used to ascertain the mineralogical, textural and petrophysical character of samples. The chief mineralogy of all samples is calcite (99%) (Table1). Limestone rock is highly heterogeneous with selective, but varying degrees of dissolution activity. We first saturated the samples with brine (8000 ppm NaCl) at vacuum (– 27 mm of HG) with no external pressure to achieve benchtop (partial) saturations of about 50% or more. The cores were again saturated at 1000 psi (undrained) confining pressure to achieve pressure (complete) saturation. Figure 1 shows the schematics of the experimental setup for both benchtop and pressure measurement and the basic difference between static and dynamic measurement setups in lab. Dynamic measurements at dry, benchtop and pressure saturations were carried out using 1 MHz (ultrasonic) transducers. Transducers were put on the flat opposite ends of the samples. Table 2, and Table3 presents measured data for compressional and shear-wave velocity and elastic moduli.

#### b) Literature Data

Literature data was taken from Adam et al. (2006). It consists of carbonate rocks from two reservoirs in the Middle East. Samples are measured at seismic (3-1000 Hz) and ultrasonic (0.8 MHz) frequencies; under dry, liquid-but butane (a light hydrocarbon) and brine (180000 ppm NaCl) saturations. The differential pressure varied from 3.5 MPa

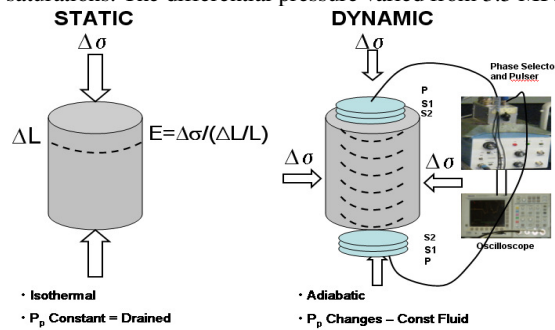


Figure 1: Schematics of experimental set-up for static and dynamic acoustic measurements in lab.

**Table1.** Composition and porosity of carbonate samples

Sample	Calcite (%)	Clay (%)	Quartz (%)	Gr. Den. (g/cc)	Porosity (%)
D	0.99	0.01	0.00	2.71	28
J	0.99	0.01	0.00	2.71	20
K	0.99	0.01	0.00	2.71	29

J-homogeneous; D,K- heterogeneous

**Table 2.** Elastic Properties at Partial Saturation (PS)

Sample	Vp at PS (m/s)	Vs at PS (m/s)	K at PS (GPa)	μ at PS (GPa)
D	3750	2040	18.27	8.47
J	3050	1550	14.66	5.46
K	3100	1750	11.73	6.10

Vp- Compressional Velocity, Vs- Shear Velocity

**Table 3.** Elastic Properties at Full Saturation (FS)

Sample	Vp at FS (m/s)	Vs at FS (m/s)	K at FS (GPa)	μ at FS (GPa)
D	3820	2000	19.6	8.71
J	3390	1590	18.99	6.0
K	3200	1600	14.72	5.58

K- Bulk Modulus, μ □ Shear Modulus

31 MPa. The detailed petrographical data on these samples can be found in Adam *et al.* (2006).

#### Fluid and Frequency Effects

Carbonate rocks are very sensitive to matrix alteration and can undergo diagenesis. These diagenetic activities can change the petrophysical properties of the rock and in some cases the total morphology of the rock may be altered (Eberli et al., 2003). This problem is more evident in unconsolidated shallow carbonate reservoirs with loose cementing material to bind the matrix. Fluid substitution and frequency of investigation is important for oil fields undergoing enhanced oil recovery (EOR) or other secondary recovery schemes. Knight et al (1998) showed that saturation heterogeneity caused by lithological variations can lead to distinct dependence of velocity on saturation.

Figure 2a shows the measured effective bulk modulus data on one of the Middle East samples in dry and in fully butane- and brine- saturated states at frequencies ranging



from seismic to ultrasonic. The rock effective bulk modulus increases with frequency (*i.e.* it shows dispersion) especially for brine saturation, while there is negligible dispersion when the rock is saturated with butane or in dry state (Adam et al. 2006). Figure 2b plots the shear modulus of another carbonate from the Middle East as a function of differential pressure and saturant. Two main observations are drawn. First, the shear modulus can either weaken or strengthen with brine saturation compared to the dry rock. At 100 Hz, we observe shear modulus weakening from dry to wet, while for 0.8 MHz data the shear modulus strengthens when brine fills the pore space (Adam et al. 2006). The authors suggest that there is more than one rock-fluid mechanism active in the rock. Second, the shear modulus weakens more for low- than for high-differential pressures. From Figure 2, it is also evident that the shear modulus sensitivity to brine saturation for both 100 Hz and 0.8 MHz is repeatable; the shear modulus weakening is not affected by hysteresis. This reversible weakening or strengthening of the frame is likely associated with the opening and closing of compliant pores or cracks. The authors suggest that some of these cracks are intrinsic to the rock, while others might have been induced while drilling or coring.

Figure 3a and 3b compare the dry- and brine-saturated rock shear modulus for all samples for 100 Hz and 0.8 Hz at 3.5 MPa differential pressures (Adam et al. 2006). The high porosity (24-30%) samples have shear modulus around 10 MPa, while the low-porosity samples have a shear modulus larger than 15 MPa. The shear modulus for brine saturated rocks at ultrasonic frequencies is greater than for seismic frequencies. This comparative strengthening could describe modulus dispersion as a result, for example, of global- and squirt-fluid flow in the pore space. However, for samples showing lower shear modulus, the chemical softening of the rock could be dominating over the modulus dispersion. The authors also propose that the ultrasonic-wave velocity represents the fastest path (stiffest area in the rock). If the chemical weakening is occurring in an isolated area of the sample, the stress-strain experiment measures the effective rock deformation (frame softening), while the ultrasonic wave will propagate in the unperturbed rock. Figure 3c and 3d show comparison of variation in shear modulus at 3.5 MPa as measured at seismic frequencies for brine and butane saturated rocks. Relative to brine saturated state, there is no variation in shear modulus in butane saturated samples.

### Heterogeneity Effects

Figure 4a and 4b presents the scanning electronic microscope (SEM) analysis of heterogeneous sample homogeneous samples respectively. It is evident that the samples have poor grain size sorting and multi-porosity system in addition to micro-fractures and cracks. Figure 5a and 5b presents the ultrasonic shear waveform as captured on oscilloscope. Due to the rotation of the sample from point 1 to point 5, the waveform changes noticeably for the heterogeneous sample indicating that at different point the shear-wave is traveling through different fabric plane in the sample. It is important to remember that these samples have no variation from mineralogical point of view. Therefore, the observed difference in the waveform pattern is only due to the fabric of the samples.

In carrying out dynamic measurements, interactive processes between wave energy and the rock-fluid mass causes dispersion and attenuation. Winkler et al. (1982) argued that presence of fluids in addition to microcracks can cause significant amount of wave attenuation due to phenomena like frictional sliding at grain boundaries or across crack, effect of wetting on grain boundary frictions and flow between macroscopic regions of total and partial saturation. These effects are important to be considered to properly calibrate the dynamic measurements to the considerably more accurate and reliable static measurements. In this paper we have defined a scale to measure the amount of relative heterogeneity in a sample w.r.t the dominant character (density) of the sample. This Heterogeneity Number is used to define the amount of heterogeneity in the rocks and to correlate its variation in rock samples with variation in elastic properties.

The computed tomography (CT) scan can be used for qualitative and quantitative analysis of internal morphology, if there are sufficient differences in atomic composition or density or both (Figure 5). 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 quantified the heterogeneity of the core sample on the basis of the available CT density values and compared it with the variation in measured modulus values for homogeneous and heterogeneous samples (Equation 1). We use only



those CT numbers contributing more than 5% to the bin concentration.

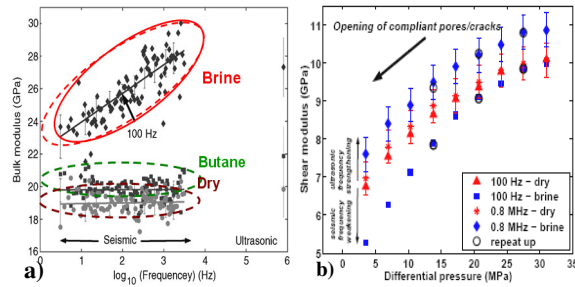
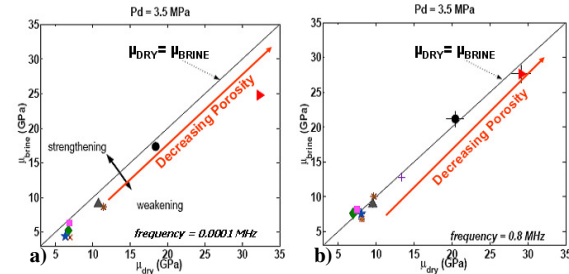


Figure 2. a) Effective bulk modulus at 31 MPa and at seismic and ultrasonic frequency with least square estimates. Dispersion is shown to be fluid dependent, b) Shear modulus weakening and strengthening at seismic and ultrasonic frequencies, respectively. (Adam et al. 2006)

#### Frequency Effects



#### Fluid Effects

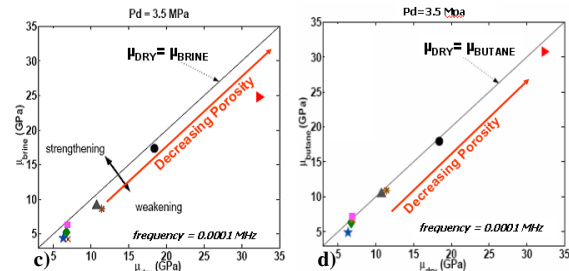


Figure 3. Shear modulus variation under brine saturation at 3.5 MPa a) at 100 Hz and b) 0.8 MHz, to show the frequency effects on measured elastic properties. Shear modulus variation at 100 Hz under saturation with c) brine and d) butane, to show the fluid effect on measured elastic properties. (modified from Adam et al., 2006)

$$Heterogeneity\ Number(\%) = \frac{1}{2} * \frac{Maximum\ CT\ Number(>5\%) - Minimum\ CT\ Number(>5\%)}{CT\ Number\ Highest\ Bin\ Percentage} * 100$$

If variation in elastic properties between the relatively homogeneous and the heterogeneous samples are comparable to the variation in heterogeneity number, correlations can be drawn to decide for the distribution of elastic properties in a reservoir geological model as a function of the variation in heterogeneity. In the present case, we find that the relation between the variation in elastic properties and the heterogeneity number is inversely proportional. However, this inverse relation can be generalized as we are dealing with only two samples in the present case. Using equation 1, the samples used in this study were found to be 43% (D) and 17% (J) heterogeneous w.r.t the dominant character (density number) of the sample.

Prasad et al., (2009) have suggested techniques to statistically quantify the variations in texture and heterogeneity in organic rich shales (ORS). The authors used the coefficient of variation (CV) of the pixel value from SAM image for quantifying heterogeneities, and spatial autocorrelation function (ACF) for quantifying the textural variation in the rock. A detailed description of the application of scanning acoustic microscope to petrophysics can be found in Prasad (2001) and Prasad et al., (2002a). We plan to use this approach to quantify the heterogeneities and textural variation in carbonates.

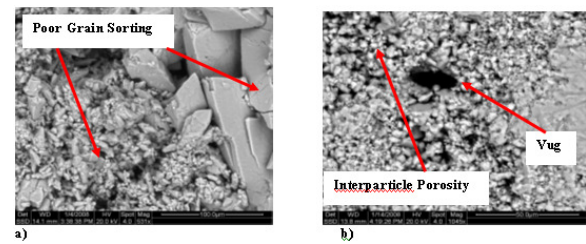


Figure 4. SEM Backscatter Images of sample a) D-Heterogeneous, b) J-Homogeneous. Dual porosity systems and poor grain sorting can be seen in both the samples.

#### Results

We report results of laboratory experiments to compare and understand the response of homogeneous and



heterogeneous carbonate rocks under similar dry, partial, and fully saturated conditions. CT scan, ESEM and well-logs are used to support our findings. The available CT scan images along with the density numbers are displayed in Figure 5a for homogeneous and Figure 5b for heterogeneous plug. The shear-wave traveling inside the sample shows that with changing orientation of the sample, the s-waveform pattern changes for heterogeneous sample, whereas for homogeneous sample, the waveform pattern is almost same for the 5 orientations. At the same time, both samples exhibit no anisotropy as the start time for the shear phase is same and well defined for all the five orientations. The only possible reason for variation in waveform response is heterogeneity (grain size and sorting, arrangement, pore size, cracks, etc. and their compliance to the applied stress) in the fabric as the mineralogy is all alike (99% calcite).

It was interesting to observe the saturation patterns in these plugs as the homogeneous and heterogeneous samples exhibit different behaviors (Figure 6). For the benchtop saturation (only under surface vacuum) the homogeneous sample could replace 97% of the air by water, whereas in heterogeneous sample it was only 44%. At pressure saturations (vacuum and 1000 psi confining pressure-undrained), the homogeneous sample gained further 2% replacement (almost complete water saturation) of the air by water, whereas in heterogeneous sample, water replaced a further 36% of the initial air volume in the core plugs. Most of change in bulk density for the homogeneous sample (+9%) was observed at benchtop saturation and it did not change any appreciable amount during the pressure saturation cycle. On the other hand, the heterogeneous sample recorded a change of +7% in bulk density at benchtop saturation and a further of +5% at pressure saturation (Figure 6).

The P-wave velocity shows variation of up to +15% and +4% for homogeneous and heterogeneous sample respectively (Figure 7a and 7b) in going from benchtop (partial) to pressure (full) saturation. The effects of saturation are more pronounced for the shear wave velocity. Most of the samples show weakening of shear modulus upon saturation. For homogeneous sample shear-wave velocity decreased up to -18% and -10% for partially and fully saturated conditions, respectively. Whereas, for heterogeneous sample, shear velocity recorded a decrease

of -8% at benchtop saturation and did not change further at the pressure saturated condition (Figure 7c and 7d).

In homogeneous sample, shear modulus decreases by 21% at benchtop (partial) saturation and increases (recovers back) by 10% at pressure (full) saturation stage (Figure 8). Similarly, shear modulus decreases by 4% at benchtop saturation by and increases (recovers back) by 3% at full saturation in heterogeneous samples. We did not observe hysteresis in the shear modulus with saturation; the changes in shear modulus reverted to their original value in most of the cases after removal of the saturant (8000 ppm brine).

### Discussions

The change in strength (elastic properties) of the rock matrix as function of saturation and time can always be a challenge for reservoir modeling and simulation purposes. The exercise carried out in this paper has an analogy to flooding of reservoirs for enhanced oil recovery. The analysis of change in capillary pressure with change in imbibition type ( $P_{cwg} = P_{water} - P_{gas}$ ) has telling effect on the wettability and relative permeability of the fluid flow and ultimately on the recovery factor.

It is apparent (Figure 8) that there is lot of uncertainty in the elastic properties of homogeneous rock to that of a heterogeneous rock as is measured (dynamic) in this exercise. Not only the amount of saturation but the pattern of it is equally important to be considered as time and saturant dependent variables for using them in reservoir simulation jobs. In this exercise we have recorded a 45% and 10% uncertainty in the estimation of bulk and shear modulus between the homogeneous and heterogeneous samples at pressure saturation stage (Figure 8). The variation in elastic moduli is much more than the proportional increase in bulk density upon saturation. At present we are not very clear about the exact phenomena for this difference in behaviour of the carbonate



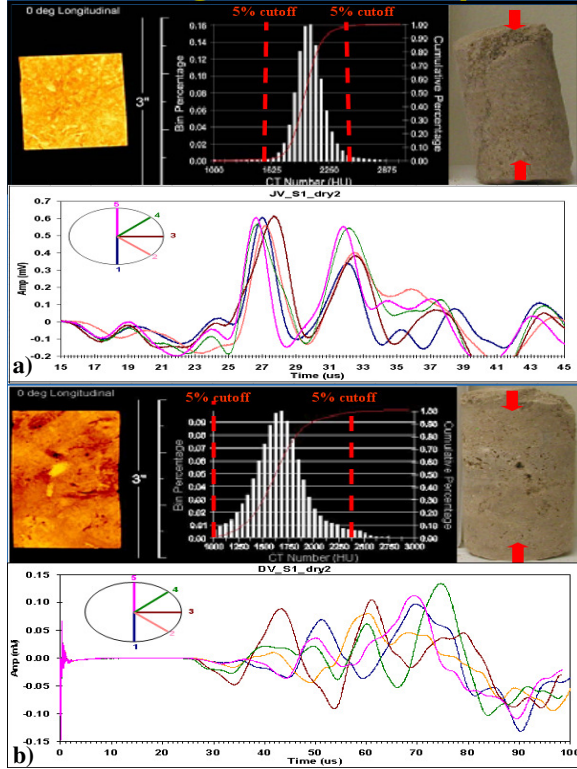


Figure 5. CT scan, CT number (HU), core image and acoustic waveform signature of ultrasonic pulse for a) Sample-D (Heterogeneous) and b) Sample-J (Homogeneous). The lower half of both the image displays the ultrasonic waveform through the sample captured on oscilloscope.

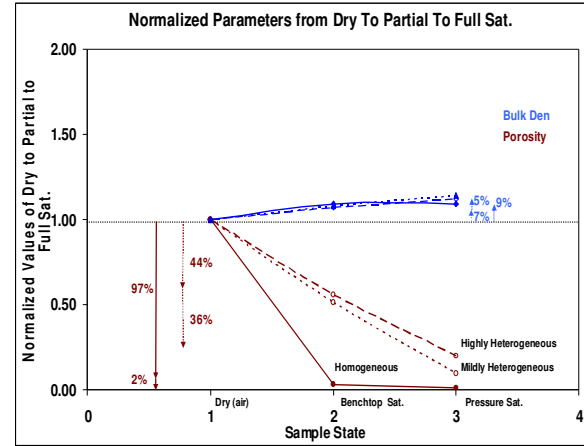


Figure 6. Variation of bulk density with variation in saturation percent (water replacing gas) at dry, partial (benchtop) saturation and full (pressure) saturation state.

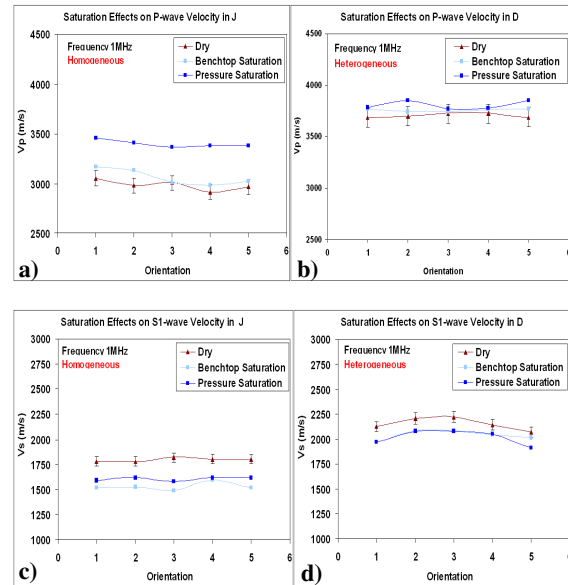


Figure 7. Velocity values at dry, partial(benchtop) saturation and full(pressure) saturation states for a) compressive-wave velocity in J, b) compressive-wave velocity in D, c) shear-wave velocity in J, d) shear-wave velocity in D.

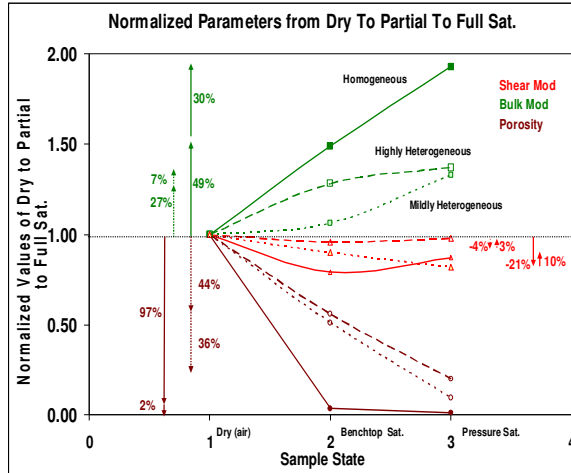


Figure 8. Variation in elastic moduli with variation in saturation percent (water replacing gas) at dry, partial (benchtop) saturation and full (pressure) saturation state.

rocks but in general it can be expressed that phenomena like surface energy reduction due to broken solid-solid bonds and the thickness of the fluid film (Khazanehdari and Sothcott, 2003) is mostly responsible for this shear modulus reduction.

The heterogeneity number (HN) as calculated from equation (1) could also explain the above observations. Low aspect ratio pores, such as cracks or elliptical pores, in heterogeneous samples offer a large part of the surface area to the fluids in the first transition from dry to partial saturation. Thus, they might have reached equilibrium much faster from dry to partial saturated state and therefore did not show much change in elastic moduli (bulk and shear) during the second transition from partial saturation to full saturation. On the other hand, in homogeneous samples, high aspect ratio pores might have caused higher tortuosity that caused the fluid to take longer to reach the entire pore surface area and might have reached equilibrium much later have large changes to observe in the second transition (partial to full saturation) also. This heterogeneity and elastic property analysis is crucial in understanding and explaining, why different parts of a same formation, in close proximity to one another, behave differently in terms of holding and transporting hydrocarbons.

This exercise can also help us in commenting on the bypassed oil that is left behind in reservoirs based on the heterogeneity distribution with in a facie or formation type. Figure 9 displays water imbibition curve (red) for standard mixed wettability rock where the domains of natural and forced imbibition are distinctly indicated. We made use of the same plot to display the difference in the bypassed oil as would be left behind if we have the similar type of homogeneous (green) and heterogeneous (blue) distribution in the reservoir (Figure 9). We are reluctant to quantify these uncertainty effects at reservoir scales as we have very limited data in this exercise. We plan verify the observation of this exercise with results from reservoir simulation to see if there is any large scale effects to be considered for predicting productivity of the reservoir.

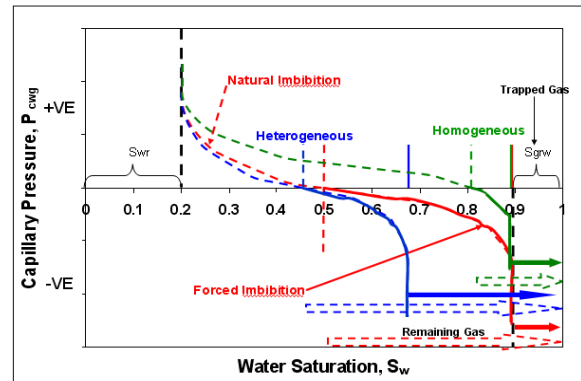


Figure 9. Water imbibition curve for mixed phased wettability rock (red color) along with imbibition curves for the homogeneous (green) and heterogeneous (blue) rock type with the saturation data from the current exercise. The figure shows the important of bypassed oil which is easy to flow in one type of rock than other.

## Conclusion

We have shown that, in carbonates, saturation with certain fluids can facilitate weakening of the matrix. This process leads to changes in the elastic strength and velocities in the reservoir rock. Given this rock physics understanding, we can define boundary conditions and provide constraints on the physical properties derived from petrophysical and seismic data that are used to populate the reservoir models. The variation in compressive and shear-wave velocity is mainly due to the changes in elastic moduli and is larger than the density effects.



It is essential to measure and understand the petrophysical and elastic parameters at partial and at full saturations as reservoirs in real time goes through both these stages during the EOR flooding programs, to make realistic reservoir models. It is also important to perform corrective fluid substitution exercises to model the fluid effects on rock physics parameters and eventually on productivity in particular under multiphase flow scenarios.

Reservoir heterogeneity is needs to be addressed to create realistic geological models for optimal reservoir simulation. Although characterization of heterogeneity at the lab scale is only a starting step, the approach can be upscaled by making observations and measurements at different frequency scales to better approximate reservoir characteristics.

### Acknowledgement

We acknowledge PI Abu Dhabi for research grant, Center of Rock Abuse for motivation, and my peers for discussion and suggestions

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