A Study of Permeability and Velocity Anisotropy in Carbonates

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Abstract

The ability to predict permeability anisotropy through seismic can assist engineers in having a deeper understanding of fluid flow dynamics and developing oil fields. However, carbonate rocks, which constitute important petroleum reservoirs in the Middle East, have complex textures and properties distribution due to their diagenetic processes. Indeed, relationships between seismic properties and permeability need to be better understood. Hence, this study investigates the relationship between permeability and seismic velocity anisotropy. An experimental procedure to measure this anisotropy on a set of samples from a carbonate reservoir is presented. The relationship between permeability and seismic velocity is complex. Compressional (P-wave) velocity response was found to be independent of permeability anisotropy. However, a trend was observed between the shear (S-wave) velocity and permeability at each measurement location in some samples. An inverse relationship was found between shear velocity and permeability when the velocity is measured perpendicular to the preferential permeability direction, whereas the relationship was proportional when the velocity is measured parallel to the preferential permeability direction. This could have important applications in application of seismic multicomponents integrated to reservoir simulation.

1. Introduction

Carbonate rocks constitute important petroleum reservoirs in the Middle East. These rocks are characterized by complex textures and properties distribution such as permeability that resulted mainly from the various diagenetic processes such as dissolution, cementation, and precipitation. These complexities make it difficult to understand the relationships of seismic velocity and permeability for carbonate rocks. Accordingly, the ability to predict permeability anisotropy of carbonate reservoirs may assist engineers in developing oil fields and having a deeper understanding of the dynamics of fluid flow. The petrophysical properties of reservoir formations containing hydrocarbons dictate the quantities of fluids trapped within their pore space. The ability of these fluids to flow through rocks together with the ability of rocks to transmit fluids via the interconnected pores is called permeability. Permeability is considered one of the most important petrophysical rock properties as it is essential to estimate flow rates and fluid recovery. Most experimental studies conducted in laboratories to understand rock properties have been carried out on sandstones [1]. However, applying the relationships developed for sandstones to carbonate rocks is challenging as it works in only some cases and it does not work in others. From the engineering point of view, rock heterogeneity, which is common in carbonate reservoirs, makes it difficult to obtain representative permeability of the reservoir formation far away from the wellbore.

In this paper, an experimental procedure to measure permeability anisotropy on a set of samples from a carbonate reservoir is presented. The paper investigates the relationship between seismic wave velocities and permeability anisotropy for each sample. Finally, it is found that an inverse relationship between shear velocity and permeability when the velocity is measured perpendicular to the preferential permeability direction, whereas the relationship was proportional when the velocity is measured parallel to the preferential permeability direction.

Bastos et al. [2] established a relationship to estimate permeability from seismic wave velocity for an offshore Brazilian field. Measurements of compressional wave velocity and shear wave velocity were made on limestone core samples and supplemented with measurements of porosity and permeability. Using this experimental data, Bastos et al developed empirical relationships between permeability and porosity and between compressional wave velocity and porosity. Then, Bastol et al used these relationships to estimate permeability from compressional wave velocity.

Fabricuis et al [3] found that permeability of carbonate sedimentary rocks can be estimated from information on porosity and the ratio of compressional velocity to shear velocity (υ_p/υ_s). Fabricuis et al also found that for dry rocks, the velocity ratio (υ_p/υ_s) and permeability are both dependent on porosity and the specific surface of the sediment.

Assefa et al [4] conducted some measurements on oolitic limestones of the Great Oolite Formation of southern England. Measurement parameters included permeability, compressional wave velocity and shear wave velocity. Velocity measurements were carried out using a pulse-echo method. These measurements were made under a simulated in situ condition of pressure in vacuum dry and fully saturated conditions. Assefa et at found that both compressional wave velocity (υ_p) and shear wave velocity (υ_s) decrease with increasing porosity and that compressional wave velocity decreases approximately twice as fast as shear wave velocity. However, no apparent relation was observed between seismic wave velocities and permeability during this study.

2. Experimental Procedure

The experimental procedure perused in this study consisted of two steps. The first step was to conduct permeability measurements on eight locations on the upper surface of a core plug sample, and the second step was to measure seismic velocity on the same locations. These measurements were made on nine carbonate rock samples from one reservoir in the Middle East. Measurements were made at bench top conditions and when the samples were dry. The core plug samples were cylindrical and had dimensions of 1.5 inch in diameter and length ranging between 1 inch and 3 inches.

2.1 Permeability Measurements

Permeability measurements were taken on nine locations on the upper surface of each core plug sample. These eight locations were determined by dividing the circular surface of the sample into eight equal divisions, and measurement points were taken to be the central point in each division. A ninth point was taken to be at the intersection of all divisions which is the center of the circular surface, designated by location #0. Point permeability of the nine locations was measured using a point permeameter called Pressure Decay Profile Permeameter (PDPK-200). Measured permeabilities ranged between 0.1 mD to 120 mD. The measurement points are shown in Figure 1.

The permeameter used (PDPK-200) measures nitrogen gas permeabilities reliably form 0.001 mD to 30,000 mD and measurement time varies across different measurement locations from 2 seconds to 30 seconds. PDPK-200 also corrects the measured gas permeability for nitrogen gas slippage (Klinkenberg) and inertial resistance (Forchheimer). Klinkenberg correction is performed to estimate liquid permeabilities from measured gas permeabilities at different pressures. Klinkenberg found that gas permeability depends on pressure and that an inverse linear relationship between permeability and pressure exists. Gas slippage effects occur due to the fact that gas density and viscosity is much less liquids' density and viscosity. Therefore, to account for this fact, liquid permeability is estimated by plotting gas permeability versus inverse pressure, and then extrapolating the straight line to the point where pressure equals infinity (1/P = 0). At this pressure, it is assumed that gas behaves as liquid. This technique is illustrated in Figure 2.

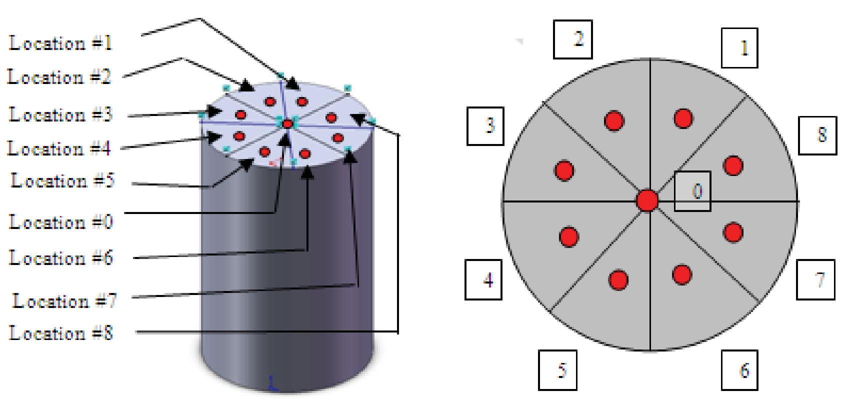

Figure 1. D view and Top view of permeability measurement points on a core sample.

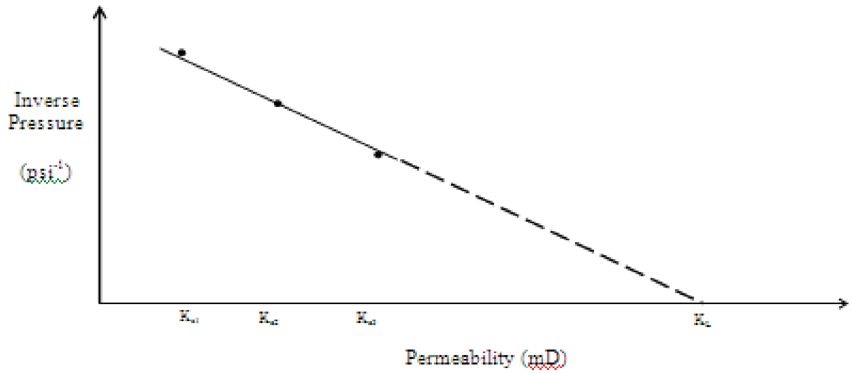

Figure 2: Estimating liquid permeability from gas permeability (Klinkenberg Effect)

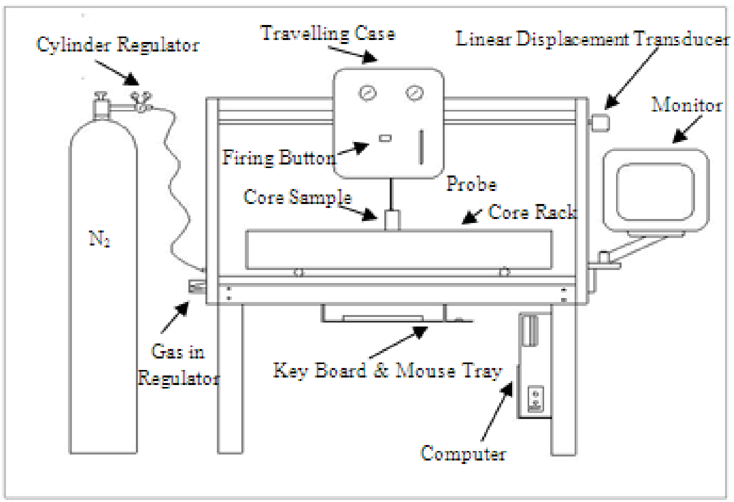

Figure 3. The main components of PDPK are Table and Frame, Travelling Case, Core Rack, and External Nitrogen Computer.

The main components of the PDPK-200, shown in Figure 3, are:

- Table and Frame
- Travelling Case
- Core Rack
- External Nitrogen Supply
- Computer

The probe assembly and core rack are moved to the desired measurement location on the sample's surface. Then, the probe is lowered pneumatically where its rubber tip seal is pressed against the sample with a controlled pressure. This requires that the surface of the sample be smooth to allow for proper sealing with the measuring probe. It is noteworthy to mention that in some samples, there was an apparent crack near some of the measurement locations. This caused the permeability measurement to be largely high and in considerable error, as these cracks provided paths for nitrogen gas to escape through. These erroneous permeability measurements were not considered in the plots and diagram in this study.

2.2 Seismic Velocity Measurements

The velocity of seismic waves, both compressional (υ_p) and shear (υ_s), was measured along radial lines passing through the locations of the points where permeability measurements were conducted. However, measurements were only taken along five lines because the measurements on the location lying on the other end of the each measurement line will have the same velocity value. This is because the phase shift between the two ends of the measurement line is π. Seismic velocity waves were measured by attaching two transducers to both ends of the sample through the use of a resin coupling. The purpose of using the coupling is to magnify and strengthen the velocity signal that appears on the oscilloscope. Then, the data was transferred to a computer where it was processed to pick up the value of the velocity at each measurement line. The velocity was calculated by dividing the length of the sample by the time it took the wave to pass along the sample, subtracting from that time the delay caused by the transducers themselves. At the beginning of the measurement series, the setup was tested with an aluminum core plug and the result was compared with the published velocities for aluminum in the literature to ensure accuracy. CSM software was used to calculate the velocities. P-wave velocities were determined easier than S-wave velocities. This is because P-waves travel faster than S-waves, so when detecting the S-wave some P-wave components will arrive at the beginning before S-wave arrives. Probably, the most difficult part of the measurement series is to determine when the S-wave arrives at the receiver transducer. Therefore, to avoid this problem, all the S-waves were plotted together on the same diagram using MS Excel program as this helps identify the arrival of S-waves at each location. The measurement lines are shown in Figure 4.

Velocity measurements were conducted by placing the samples across two transducers. The two transducers are used as a dispatcher and a receiver. The dispatcher transducer converts the electrical energy supplied by the power source to mechanical vibrations that travel through the rock sample, and the receiver transducer converts the transmitted mechanical energy back to electrical energy that can be displayed digitally on an oscilloscope screen. Figure 5 shows the setup used to measure seismic velocity through samples.

Then, to explore the relationship between seismic velocities and permeability, several graphs were constructed. These graphs included compressional wave velocity and gas permeability at each measurement location, and shear wave velocity and permeability at each measurement line were constructed. Similar graphs were constructed using Klinkenberg liquid permeabilities and seismic velocities.

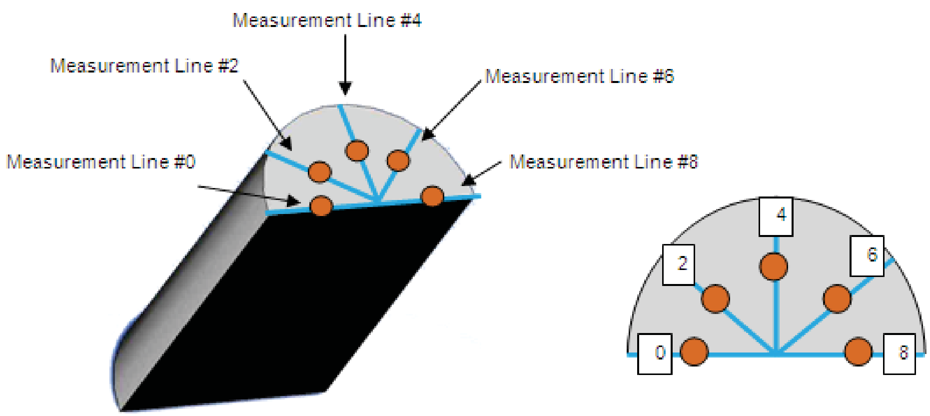

Figure 4. 3D view and Top view of velocity measurement lines on a core sample

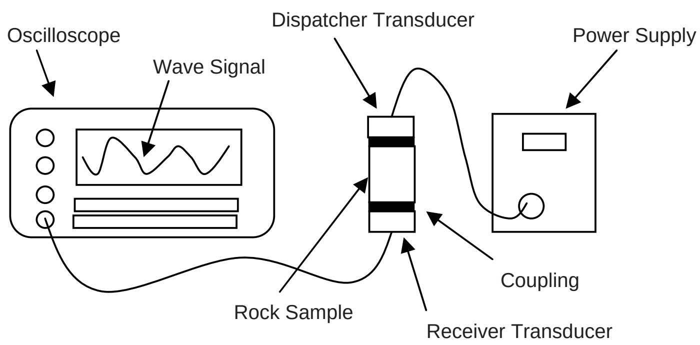

Figure 5. The setup used to conduct velocity measurements on each measurement line shown in Figure 4.

3. Results and Discussion

The data obtained from experimental measurements were analyzed by plotting permeability and seismic velocity at each location for every sample. Accordingly, six plots were generated for each sample including:

- Gas permeability and compressional wave velocity plot,
- Liquid permeability and compressional wave velocity plot,
- Gas permeability and shear wave velocity (S_1-wave) plot,
- Liquid permeability and shear wave velocity (S_1-wave) plot,
- Gas permeability and shear wave velocity (S_2-wave) plot,
- Liquid permeability and shear wave velocity (S_2-wave) plot.

For all samples, it was found that compressional wave velocity response (in which particles vibrate parallel to the direction of wave propagation, as shown in Figure 6) is independent of permeability anisotropy. This implies that variations of permeability cannot be detected though analyzing compressional wave velocities through underground formations. Although small differences in the measured value of compressional velocity was recorded (in the order of few meters per second), theses differences are most probably due to experimental errors such as lacking proper contact between the transducers and the sample. Figure 7 shows an example of gas permeability and compressional wave velocity plot for sample #1.

Upon considering shear velocities (in which particles vibrate perpendicular to wave propagation direction. In 3D space, there exists two shear waves designated by S_1 & S_2, as shown in Figure 8), two groups of samples were recognized. In one group there was an apparent trend between permeability anisotropy (whether gas or liquid permeability) and shear wave velocity variation. The other group does not present this trend or it is not apparent. The first group contained 4 samples (#1, 3, 5, and 17) in which one direction of the shear wave velocities was found to be inversely related to permeability at the same measurement location, and the other direction of shear wave velocity was found to be proportionally related to permeability at the same measurement location. In other words, shear wave velocities is following permeability anisotropy through each sample (velocity is either against or towards permeability). An example of a sample that belongs to this group is shown in Figure 9A & 9B.

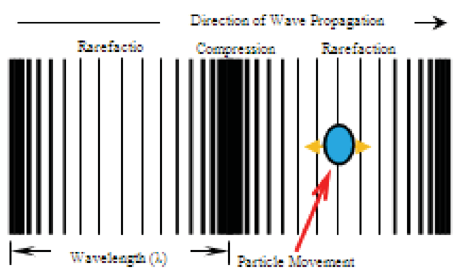

Figure 6. Compressional waves.

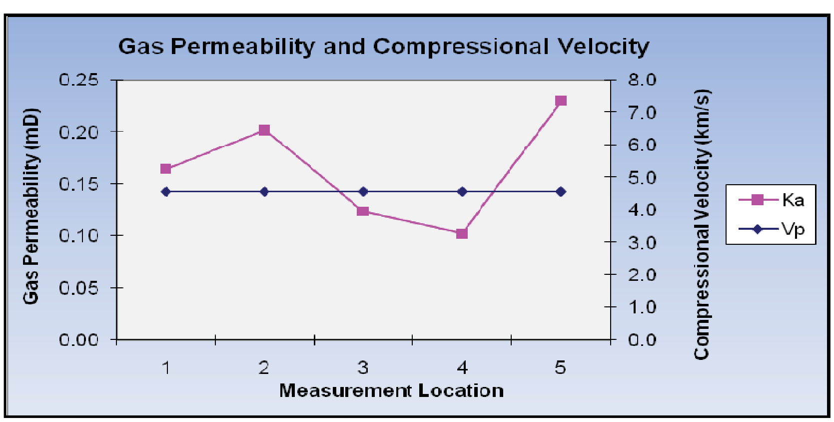

Figure 7. Gas Permeability and Compressional Velocity Plot for Sample #1. It is apparent from this chart that when permeability changes from one location to another on the sample, compressional wave velocity does not reflect that change.

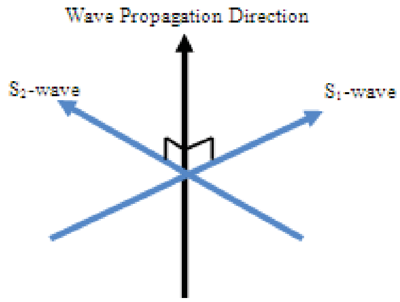

Figure 8. Shear waves.

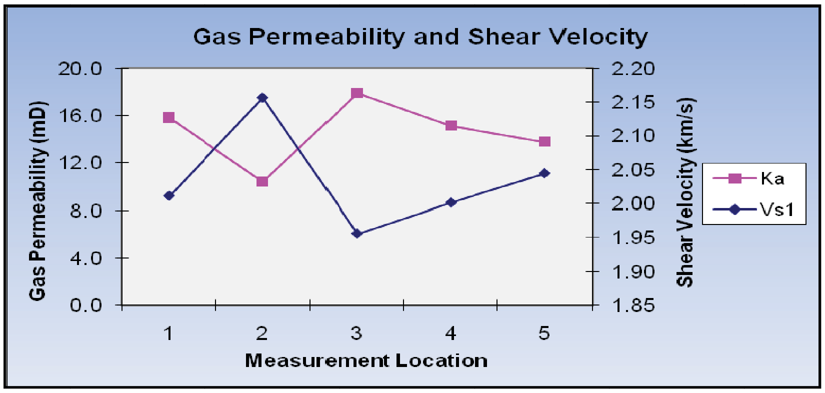

Figure 9A. Gas Permeability and Shear Wave Velocity Plot for Sample #5. It is apparent from this chart that an inverse relationship may exist between permeability and shear wave velocity (S_1-wave) measured at the same location.

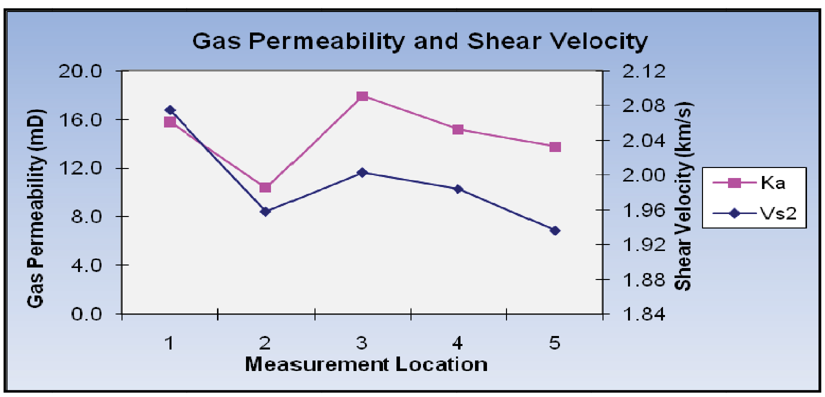

Figure 9B. Gas Permeability and Shear Wave Velocity Plot for Sample #5. It is apparent from this chart that a proportional relationship may exist between permeability and shear wave velocity (S_2-wave) measured at the same location.

High permeability zones are merely pores that are connected to each other, and these pores might be connected in a certain preferential direction creating directional permeability. These pore spaces in the reservoir contain fluids either hydrocarbon gas or liquid (oil or water). When the shear wave travels parallel to the preferential permeability direction, it passes through solid rocks and pore throats smoothly, reflecting this path through high velocity. On the other hand, when the shear wave velocity travels perpendicular to the preferential permeability direction, the vibrations of the solid and fluids particles are perpendicular to the permeability path delaying the wave speed.

Hence, from the discussion above it seems that the relationship between permeability and shear velocity is best manifested in samples where one direction of shear wave velocity measurement was taken perpendicular to the preferential permeability direction, in which case, it shows an inverse relationship.

The other direction of shear wave velocity measurement was taken parallel to the preferential permeability direction, in which case, it shows a proportional relationship. This is illustrated in Figure 10.

The second group, which consisted of 5 samples (#9, 12, 13, 15, and 16), did not display such a trend clearly or this relation does not exist. An interpretation for this would be that the shear velocity measurements were neither perpendicular nor parallel to the preferential permeability plane; therefore the trend was not apparent. Another interpretation could be that permeability within these samples was random, or more complex, or not in the same plane of S-wave vibrations and permeability measurement locations. However, futher investigation is needed. Figure 11 and Figure 12 show example plots for samples #12 and #15 that belong to this group.

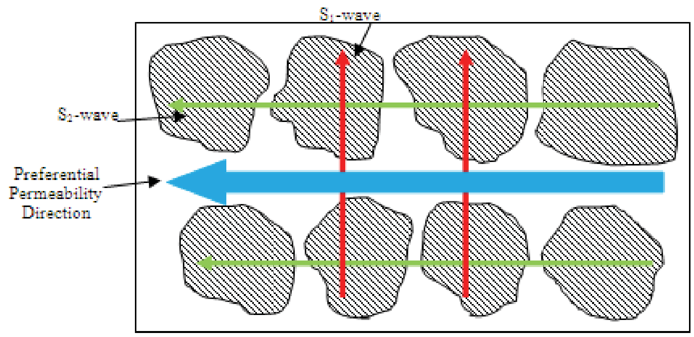

Figure 10. S1-wave propagating perpendicular to preferential permeability direction, and S2-wave propagating parallel to preferential permeability direction.

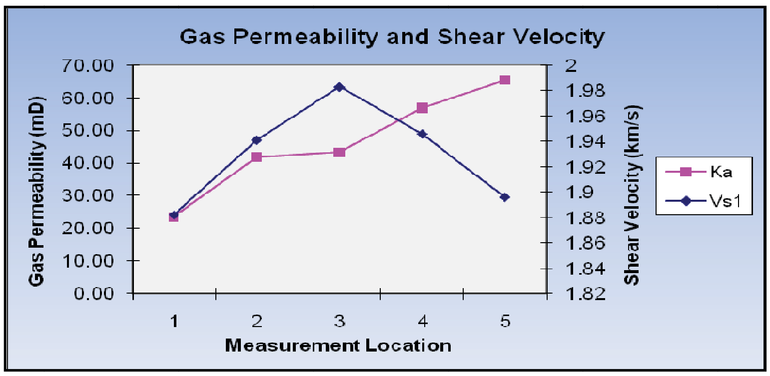

Figure 11. Gas Permeability and Shear Velocity Plot for Sample #12. From this chart, the relationship of permeability and shear velocity measured at the same location is not apparent. The trend is clear if you consider measurement locations #3, 4, and 5. Whereas, the trend is not present in measurement locations #1 and 2.

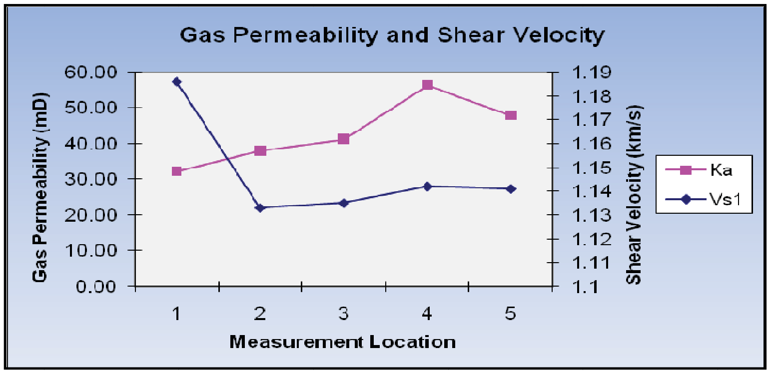

Figure 12. Gas Permeability and Shear Velocity Plot for Sample #15. From this chart, the relationship between permeability and shear velocity measured at the same location does not exist. This is probably due to the random or more complex distribution of permeability within the sample.

4. Conclusions

It is concluded that there is a potential relationship between permeability and shear velocity in some carbonates. There is an apparent trend in samples where velocity measurements had been made perpendicular to the direction of preferential permeability. Other samples do not show this trend either because velocity measurements were not made perpendicular to the direction of preferential permeability, or because permeability in these samples was random and did not have a preferential direction. However, experimental measurements on more samples need to be conducted in order to collect more data and better understand the nature of this relationship.

If a relationship between permeability and shear velocity was to be established, then this may assist in permeability prediction from seismic waves shot during exploration of hydrocarbon reservoirs. This could potentially reduce the cost of obtaining data and increase savings. Another potential application would be in reservoir modeling, where permeability anisotropy data predictions could be used in a simulation package such as Eclipse in order to predict preferential directions of water front in reservoirs.

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Author Biographies

Mr. M. Saleh is a Junior Student of petroleum engineering at The Petroleum Institute. He is the secretary of SPE student chapter at the Petroleum Institute 2008-2009. He is also the administrative assistant of the Petroleum Institute Student Council.

Dr. M. Prasad is a Professor in petroleum engineering at Colorado School of Mines. She holds a Ph.D in geophysics from the University of Kiel in Germany, 1990. Manika's Ph.D. work focused on attenuation, energy loss mechanisms and velocity dispersion in dry and fluid saturated sands. A major emphasis of Manika's work was on acoustic microscopy of rocks and ceramic composites.

Dr. S. Vega is an Assistant Professor of Petroleum Geosciences at The Petroleum Institute. She holds a Ph.D in geophysics from Stanford University, 2004. She is a petrophysicist experienced in acoustic lab measurements, correlation between geophysical data (seismic, well logs, and lab) and rock properties, rock physics model for fluid substitution, rock physics diagnosis for reservoir characterization, and anisotropy detection.

Mr. R. Sharma is a Ph.D. Student at Colorado School of Mines. Mr. Sharma have been conducting experimental studies on carbonate rock samples and investigating the relation between permeability and seismic velocity both at bench top conditions and under pressure.