Scientific Journal of Impact Factor (SJIF): 5.71
e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 5, Issue 02, February -2018

Determination of Mechanical and Petrophysical Properties of Sandstone Reservoirs Using Compressional and Shear Waves

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ABSTRACT:- *In the evaluation of a petroleum reserve, it is necessary to determine accurately certain petrophysical properties such as porosity and permeability of the reservoir rocks under different compaction conditions. These properties are affected by the relevant physical properties and such physical properties and mechanical properties affect the drilling programs and the development plans for a reservoir. It is more convenient to use homogenous rock samples with nearly constant initial permeability, obtaining such cores is very difficult. In this paper a simulated natural and homogeneous compacted sandstone rock with known physical and petrophysical properties were used. The physical properties include grain size, cementing material concentration, and compaction (confining) pressure. The effect of these properties on the petrophysical properties of Rock such as permeability and porosity were also known. For the same simulated natural sandstone rocks, Sound wave velocity was measured using an ultra sound tool. Good relationships have been developed between sound wave velocity and other rock properties; porosity, permeability, cementing condition and grain size distribution at different confining pressures. The sandstone cores have been grouped according grain size to five groups ranged between 45 and 300 µm mixed with different concentrations of cementing material. The mixture was compacted at three different compaction pressure ranges from 11000 to 23000 psi. These varying lithification factors gave these sandstone rocks a wide range of petrophysical and physical properties. The results of this study were presented as graphs of simulated lithification factors, porosity, and permeability versus sound wave velocity.*

Sonic logging data; compressional wave travel time (Δt_p) and shear travel time (Δt_s) are tested to investigate the type of reservoir fluids. Ratio ($\Delta t_p/\Delta t_s$) or V_P/V_S has shown higher sensitivity than relying only on shear wave or compressional wave data to study change of reservoir fluids from water to oil and to gas. Reliable reservoir fluids identification depending on the ratio ($\Delta t_p/\Delta t_s$) has been mainly attributed to the different physical response of compressional wave and shear wave to change of fluids from oil to gas in the presence of water in the reservoir. Field examples from sandstone reservoirs showed that sonic ratio ($\Delta t_p/\Delta t_s$) helped to identify the type of reservoir fluids gas, oil and water. Results of well testing data for studied wells confirmed the capability of V_P/V_S cross plot technique in identifying types of reservoir fluids.

Keywords: *Sonic waves, porosity, permeability, compaction pressure, reservoir fluids and sandstone reservoirs*

INTRODUCTION

Physical properties and petrophysical properties are essential elements in presenting the characteristics of reservoir rock. The relationship between these two properties are fundamental in a way that petrophysical properties influenced by the physical properties of rock, both quantitatively and qualitatively. For instances, porosity and permeability are created due to variations in grain sizes, grain sorting and cementation and compaction of induced diagenetic. Porosity and permeability are highly influenced by the porous structure. The pore framework such as pore shape, pore size, pores connections, pore wall and pore distributions, are mainly created or altered by the complex chemistry between grains, matrixes and cements. Furthermore, the overburden pressure increases the stress in grain framework of reservoir rock. Compaction pressure may contribute to both increment and decrement of porosity and permeability. Overburden causes the load-bearing grain to be compacted and tightly closed, resulting in pore reduction. Permeability also will be affected by the same compaction mechanisms where fluid flows will be limited by the reduced pores. Nevertheless, once the load-bearing grain experiences maximum compaction, rock will experience shear forces and induces fractures. This further causes high permeability by opening flow path of fluids along the shear cracks [1-3].

Porosity-dependence of seismic velocity is one of the way to understand the porous behavior numerically. The interplay between acoustics and petrophysical of any lithology provides a better understanding of the major geological factors that affect acoustic properties. Rocks often show acoustic velocity increment when rock experiences volume and porosity under compaction pressure. In porous media, elastic wave velocity is significantly attenuated by rock density and the presence of pore fluid. This can be explained because of the resistance against compression created by pore fluid. This paper will highlight the relationship between porosity and permeability of sandstone core sample and acoustic velocity under various compaction pressures, presented in correlations. The physical and petrophysical properties values will be employing records from previous study, where porosity and permeability measured at different cementing and pore size distributions. Core samples are also utilizing data from previous study [4, 5].

Oil recovery reflects the mobility of hydrocarbons through porous media. Reservoir rocks, fluid properties, and pressure gradient control this mobility. Oil-in-place is calculated either by the volumetric method or by material balance equations. The recovery factor (RF) is determined from displacement efficiency studies or from correlations based on statistical studies of types of reservoir mechanisms [17,20]. A thorough analysis of a standard suite of open-hole logs can yield a quantitative assessment of oil, gas and water saturations. This is important information when all three fluids exist intermingled within a reservoir. Porosity, together with fluid saturations, both in the flushed zone and uninvaded zone, can be evaluated.

Analytical approaches were developed that are extensions of conventional log analysis methodologies [22, 24]. Estimates of water saturation are needed when evaluating the potential of a reservoir. The problem facing the log analyst is to find a suitable equation for estimating the pore volume of the reservoir rock that is filled with water. It is generally assumed, unless otherwise, that the pore volume not filled with water is filled with hydrocarbons. The water saturation can be computed from numerous interpretation methods available. All these methods relate water saturation to resistivity, porosity and/or formation factor, and shale volume (V_{sh}); but few relate this parameter to velocity since the velocity of seismic waves is strongly dependent upon pore fluid [16, 19, 26].

The presence of compressible fluid, gas, in pore space of rock is known to have considerable influence on parameters like acoustic velocities and Poisson's ratio. Sonic travel time of compressional wave is generally used as porosity tool for given lithology. Introducing shear wave travel time is very helpful in determining mechanical rock properties. It is found that compressional wave velocity is a key for lithology and porosity prediction in petrophysical analysis (sonic logs). Shear wave velocity is very useful in determining mechanical rock properties. In oil and gas reservoirs, compressional wave velocity decreases and shear wave velocity increases. The increase of shear wave velocity is due to the decrease of density and the absorption of deformation by oil in pores and the decrease of compressional wave velocity is due to the decrease of bulk modulus of reservoir rocks; therefore, the V_P to Vs ratio, V_P/V_S, will decrease and it is more sensitive to change of fluid type than V_P or Vs separately. The use of V_P/V_S is a key parameter in reservoir study and it plays a key role especially for lithology and fluid type prediction methods [21, 23, 27, 28, 30]. Recent work suggests that the V_P/V_S ratio may also serve as an indicator of bypassed oil in cased wells. Research on the acoustic properties of heavy oils indicates that under the proper conditions of temperature and viscosity, these oils may behave as solids and generate shear waves that may be detectable at different logging-tool frequencies [25, 29]. Field examples from sandstone reservoirs have been analyzed to test the applicability of sonic ratio ($\Delta t_p/\Delta t_s$) has been determined using shear wave and compressional wave data. $\Delta t_p/\Delta t_s$ ratio was used to identify the type of saturating fluids (oil, water and gas) in logged wells in the sandstone reservoir.

EFFECTS OF DIFFERENT FACTORS ON POROSITY AND PERMEABILITY OF ROCK

EFFECT OF GRAIN PROPERTIES

Porosity and permeability are the main features in petrophysical study. Grain size such as arrangement, size, shape, roundness and grain sorting govern the quality and quantity of primary porosity and permeability in clastic rocks. Hypothetically, porosity is inversely proportional to grain size. Increment in grain size will lead to decrement of pore spaces between grains, and vice versa. This is by having a substantially greater volume of open spaces in finer grains that those composed of coarse grains. Besides, finer sands tend to be more angular in shape as it is the by-product of weathering. Finer grains are also said to be systemized in a less dense filling. Hence, they exhibit more prominent porosity compared to coarse grains.

Sandstone permeability, however, function directly proportional to grain size whereby permeability increases when the large grain sizes open flows for the fluid current to pass through. Sortation between two large grain sizes create larger pore throat, while finer grains will create small throat. This is because finer-grained tend to fill in the voids between sand grains. Due to this, distributions of small grained sands will reduce the permeability by increasing the tortuosity. A substantial increase in rock permeability increases with grain sizes, regardless of compaction pressure and cementation ratio.

Effect of the Degree of Cementation

Cementation occurs in fissures or void spaces. Cementation encompasses ions transported in groundwater, chemically react with sediments and create 'bridges' between the original sediment grains and thus, binding them together. The minerals may have derived from the sediments itself by leaching or re-deposition or may also be derived from salts dissolved in interstitial or circulating water. Due to the filling-cements in pores, porosity reduces significantly. In addition, developed cementation after deposition causes a considerable reduction in permeability. The cementation is formed either through chemical reaction between the formation water and unstable grains or by circulation in the pore spaces of solutions under hydrodynamic forces.

Effect of Compaction

Deposited sediments are subjected to compaction from their own weight and weight applied by any additional sediments deposited on top of them, hence, reducing the pore volume. The grains are compressed and become more tightly together. Eventually, the compaction that creates certain mechanical arrangements of grains and new pore system framework, causes the permeability restricted by volume reduction. The magnitude of compaction also depends on the initial porosity, sedimentation rate and time passage. In addition, reduction of permeability as a function of compaction is occurring in larger grain size as compared to smaller grain size.

SAMPLE PREPARATION/METHODOLOGY

The simulated sandstone core samples were organized according to grain sizes, ranges between 75 to 500 µm, and prepared using red to brown colored uniformed sorted sand (from Kharj area, Saudi Arabia). After sieving, sand grains are further categorized into five groups whereby sand grains range between 90 to 275 µm. The classification is meant for mean grain size range. Sodium silicate solution is utilized as a cementing material. With specific gravity of 1.4, the concentrations of sodium silicate solution are prepared into 4%, 6% and 8% in weight percentage. The solidification of sand – cement mixture was compacted at 300 oc, whereby manipulated compaction pressure extends from 11000 and 23000 psi. Existing rock permeability and porosity results for the sandstone core samples were made available. This study implementing Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT-6), an ultrasonic tool that generates ultrasonic pulses [7-9]. Measured time travel through the sample was recorded. Sound wave velocity was determined from the relation of sound wave velocity reciprocal to travel time ($V_P=1/\Delta t$). Empirical correlations were established between sound wave velocity and porosity and permeability of sandstone core samples for varied compaction pressure and cement concentrations.

RELATION BETWEEN ACOUSTIC PROPERTIES AND MECHANICAL PROPERTIES

COMPACTION PRESSURE

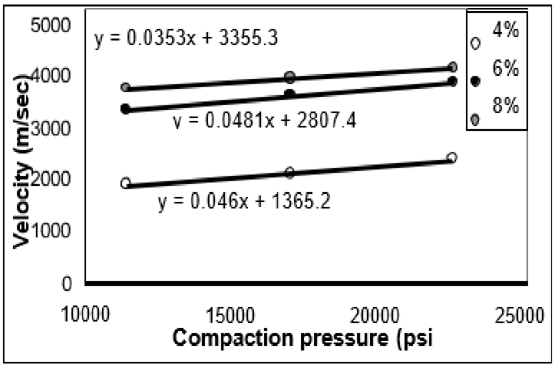


Figure 1 Compaction pressure versus sonic velocity at varying cementation.

Fig 1 shows sound wave velocity is directly proportional to compaction pressure. Hypothetically, the higher the magnitude of compaction pressures towards porosity, the higher the velocity of ultrasonic wave. In addition, the decrement profiles of sound wave velocity are observed when the cementation degree are reducing.

Mean Pore Size

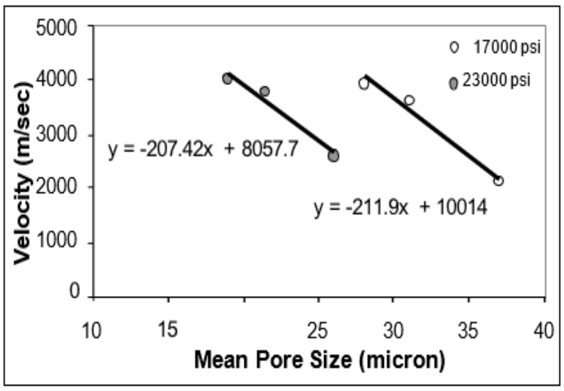


Figure 2 Mean pore size versus sonic velocity at varying compaction pressure.

Pore patterns of clastic rocks affects not only porosity and permeability of rock and fluid distribution in pore spaces but also most of the measured physical properties such as ultrasonic wave velocity and electrical resistivity. Pore pattern is comprised of pore size, pore shape, and character of pore wall, and connection between pores and distribution of larger pores sand their relations to one another. Pore size has a pronounced effect on ultrasonic wave velocity. Tests analysis has shown that ultrasonic wave velocity decreases with larger pore size. **Fig 2** illustrates this behavior at two compaction pressures. The computed results reflect that a porosity increase and then more effect of the fluid filling pores on the velocity measurements.

Permeability

Larger porosity corresponds to a greater permeability, but this is not always the case. The shape and pattern of pores, as well as the pores continuity and quantity, influences the permeability of rock. Rock permeability is not only influenced by the grain shape, size and distribution, but also affected by temperature and hydraulic gradient. Compaction and cementation obviously contribute to the reduction of permeability based on primary porosity. Solution channels, fracturing, joint planes and bedding planes, however, increases the permeability.

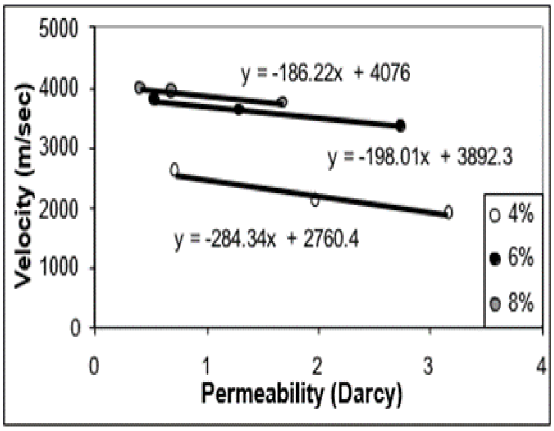


Figure 3 Rock permeability versus sonic velocity at varying cementation ratios

The permeability was measured using liquid permeameter and the recorded data were utilized in evolving the correlations. Permeability can be derived from resistivity gradients, formation tester (FT) data, Nuclear magnetic resonance (NMR) and Ø-Swi charts. In this segment, permeability can be derived from the ultrasonic wave velocity measured from core samples. **Fig 3** illustrates the decrement trend of ultrasound wave velocity as a function of decreasing permeability for different percentage of cement concentration.

RELATION BETWEEN ACOUSTIC PROPERTIES AND PETROPHYSICAL PROPERTIES

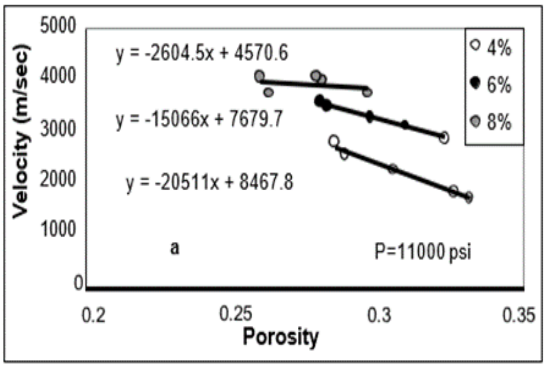
An acoustic property of a rock is the product of its wave velocity and density. It is an inherent property and depends on the elastic properties of the rock and rock density. In this section, we will examine the relationship between ultrasonic wave velocity and porosity and permeability using the same sand core samples that was produced under different compaction pressure and with different cement percentages [10,11].

Porosity

PUNDIT tool was measures the travel time transmitted through core sample, that influenced under confining pressure. Porosity was measured for the samples in the laboratory using gas – torsimeter. Travel time of wave propagates elastically throughout sample body. The elastic response in a porous material is substantially affected by the existence of pore fluid. Compressional velocity can be several times larger than the shear velocity in a water-saturated sediment. In qualitative explanation, this is a result of the added resistance against compression provided by the pore fluid. The elasticity depends on pore pressure depletion and pore compressibility, hence, affect the travel time reading. According to time average equation as introduced by Wyllie et al. in 1958, the interval transit time is related linearly to the porosity which expressed as:

$$\frac{1}{V_p} = \frac{\emptyset}{V_{fluid}} + \frac{1-\emptyset}{V_{solid}} \qquad (1)$$

Take note that the equation employing the *v* for compression velocity. Shear velocity does not travel through fluid medium; thus, saturation is assumed not to affect the shear modulus in porous rock.

a) 

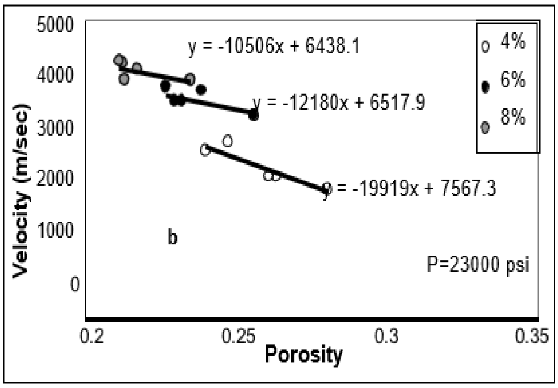
b) 

Figure 4(a-b) Rock porosity versus sonic wave velocity at varying cementation percentage and compaction pressures.

Fig 4 displays the response of ultrasonic wave velocity as a function of porosity with three different percentage of cementation concentration which are 4%, 6% and 8%, and at vary compaction pressures of 11000 psi and 23000 psi. For same porosity, the ultrasonic wave velocity readings are decreasing with the decrement of cementation concentration percentage. Decrease trends are also observed between ultrasonic wave velocity and porosity at a given cement concentration percentage and under certain compaction pressure.

RESERVOIR FLUIDS

The most important aspect in which rocks differ from homogeneous solids is in aging granular structure with voids between the grains. These voids are responsible for the porosity of rocks and porosity is an important factor in determining velocity. Seismic wave velocity is affected by rock density in such way the dense rock has higher velocity either S-wave or P-wave. Increasing of rock density indicates higher rock compaction and greater depth and overburden pressure. An empirical formula relates velocity and density takes the form (density, g/cc) $\rho = 0.23V^{0.25}$. The saturating fluids also affect seismic wave velocity. It is found that seismic wave velocity shows a significant decrease when the saturating fluids water or oil is replaced by gas.

Compressional Wave Velocity, V_P - The particle motion associated with compressional waves consists of alternating condensation and rarefactions during which adjacent particles of the solid are closer together and farther apart during successive half cycles. The relation between compressional velocity V_P and density (ρ) and elastic constants can be expressed as following:

$$\begin{aligned} V_P &= [(k + 4/3\ \mu)/\rho]^{0.5} \\ &= [(E/\rho\ (1 - \sigma))/\ ((1 - 2\sigma)\ (1 + \sigma))]^{0.5} \qquad (2) \\ &= [(\lambda + 2\mu)/\rho]^{0.5} \end{aligned}$$

where V_P, compressional wave velocity; E, Young modulus; k, bulk modulus; σ, Poisson ratio; λ, Lame constant; μ, rigidity modulus and ρ, rock density.

Shear Wave Velocity, V_S - When shear deformation propagates in an elastic solid, the motion of individual particles is always perpendicular to the direction of wave propagation. The velocity V_S of shear waves equal to $(\mu/\rho)^{0.5}$. This velocity can be expressed in terms as indicated by the relation.

$$\begin{aligned} V_S &= (\mu/\rho)^{0.5} \\ &= [(E/\rho)\ (1/2(1+\sigma)]^{0.5} \end{aligned} \tag{3}$$

where V_S, shear velocity; E, Young modulus; σ, Poisson ratio; μ, rigidity modulus and ρ, rock density.

V_P/V_S Ratio

Comparing P-wave velocity Eq. 10 and shear wave velocity equation Eq. 11 results in the following relation:

$$\begin{aligned} V_P/V_S &= [\ (\lambda + 2\mu)/\mu]^{0.5} \\ &= [(k + 4/3\mu)/\mu]^{0.5} = [(1-\sigma)/\ (0.5-\sigma)]^{0.5} \end{aligned} \tag{4}$$

where k is the bulk modulus of rock. Values of Poisson ratio σ vary from 0.0 to 0.50. Either expression tells us that the compressional velocity will always be greater than the shear velocity in each medium. If σ is 0.25, the V_P/V_S ratio equals to $\sqrt{3}$. It is worth noting that for most consolidated rock materials, V_P/V_S is between 1.5 and 2 and σ is between 0.1 and 0.33. The seismic V_P/V_S ratios for sandstones varied between 1.66 to 1.81 and for carbonates, 1.81 to 1.98.

The time average equation is often used to relate the velocity, V and porosity, ϕ as expressed in Eq. (1). Equation (5) can take the following form for P-wave:

$$1/V_P = \Phi/V_{pf} + 1 - \Phi/V_{pm} \tag{5}$$

$$\Delta t_p = \Delta t_P\varphi + (1-\varphi)\ \Delta t_{pm} \tag{6}$$

and for shear wave the form:

$$1/V_S = \Phi/V_{sf} + 1 - \Phi/V_{sm} \tag{7}$$

$$\Delta t_s = \Delta t_S\varphi + (1-\varphi)\ \Delta t_{sm} \tag{8}$$

where Δt_p is P-wave transit time and Δt_s is S-wave transit time. Seismic velocity (V_P or V_S) in the Eq. (1) and Eqs. (5-8) is a function of three variables; fluid velocity, V_f, porosity, Φ and matrix velocity, V_m. Solution of any of these equations for one variable requires the other two variables being known. In oil and gas reservoirs, compressional wave velocity decreases and shear wave velocity increases. Eq. (1) and Eqs. (5-8) can be solved for fluid velocity instead of formation porosity with the assumption of known porosity and matrix velocity.

Characterization of Reservoir Fluids Using V_P/V_S Ratio

From observation, it is found that light hydrocarbon saturation decreases the velocity of compressional wave and increases the velocity of shear wave through porous rocks relative to formation water saturation. Either shear wave or compressional is conjugate affected by rock density and elasticity. There is a smooth decrease of density with the replacement of water by light hydrocarbon or gas. Elasticity, however, is different; all deformation (expressed by μ) is readily absorbed by gas in reservoir. This is true whether the water saturation in the pore is 10, or 40, or 70%; the remaining gas absorbs deformation. Over this range of water saturation, therefore, the elasticity remains substantially constant, while the density decreases; it follows the shear velocity increases with the gas saturation increase. When the water saturation approaches 100%, the velocity must rise considerably; there is no gas left to absorb the deformation and the deformation is resisted appreciably by the water. All change between gas saturated velocities and water saturated velocities therefore occurs with the very first bubble of free gas within the pore. The fact that compressional wave is affected by change in size and deformation, the replacement of water by gas will decrease density and elasticity (change in size, bulk modulus, k and deformation, shear modulus, μ; only deformation will be absorbed by gas) in a conjugate effect; causing a decrease in compressional wave. When gas saturation reaches residual gas saturation and the water becomes the major fluid, there is no gas free to absorb deformation, shear wave will suddenly increase. On the other side, compressional wave velocity will not be much affected, and it will keep the same increasing trend with the increase of water saturation.

Field Examples

Following are examples of the application V_P/V_S ratio to identify reservoir saturation fluids in three wells in sandstone oil reservoir, Western Desert, Egypt, the used seismic data are the array sonic tool (AST) to provide travel time for compressional and shear waves. This technique can be applied for limestone or dolomite reservoir rocks. The use of

V_P/V_S cross plot has proved capable for fluid identification for given reservoir rock (same porosity and matrix) especially in gas reservoir.

Field Example A - This is gas producing well with water section at deeper depth, the well has been tested to shows fluid nature of different sections. **Fig 5** shows V_P/V_S cross-plot for Abu Rawash G unit 5 in well C, the points cluster are located far from sandstone water line which indicates gas producing unit. **Fig 6** is the V_P/V_S cross-plot for Kharita formation Unit 1 in well C, the points of V_P/V_S cross-plot lie around the water line showing that the unit 1, well C is water producing. Well test results of the two units have confirmed the interpretation of V_P/V_S cross-plot, unit 5 of Abu Rawash formation was a gas unit and unit 1 of Kharita formation was water unit.

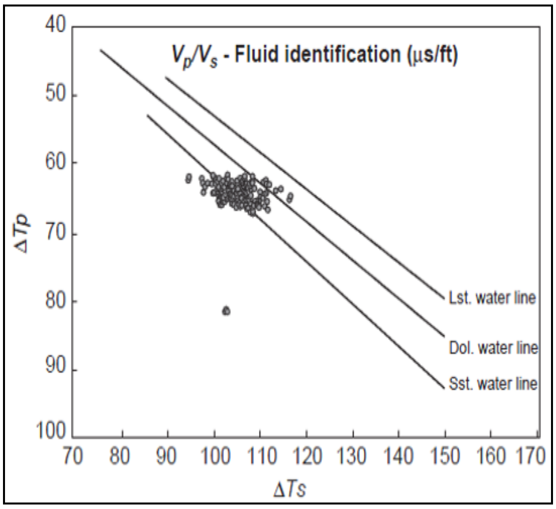


Figure 5 V_P/V_S cross-plot for unit 5-well B.

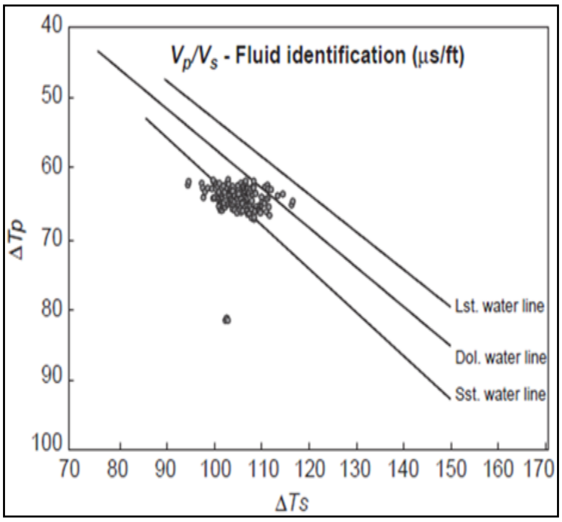


Figure 6 V_P/V_S cross-plot for unit 1-well B.

Field Example B - This example demonstrates how V_P/V_S cross-plot can distinguish between water zone and oil zone. AST data were recorded in oil producing well with lower water aquifer (Kharita formation), Western Desert, Egypt. **Fig 7** is the V_P/V_S cross-plot for in Kharita, formation E1, well D, plotted points shows very clearly that it water layer. **Fig 8** illustrates V_P/V_S cross-plot points in Baharyia formation, well D. It is observed that plotted points on the cross-plot are shifted downward from the sandstone water line. This indicated that the tested section is oil producing. The oil potential of Baharyia formation and water saturation of Kharita formation have been confirmed by well testing data.

From field examples of Western Desert, Egypt and other studies, we can confirm that compressional wave velocity is a key for lithology and porosity prediction in petrophysical analysis (sonic logs). Shear wave velocity is very useful in determining mechanical rock properties. In oil and gas reservoirs, compressional wave velocity decreases and shear wave velocity increases. The increase of shear wave velocity is due to the decrease of density and the absorption of deformation by oil in pores and the decrease of compressional wave velocity is due to the decrease of bulk modulus of reservoir rocks; therefore, the V_P/V_S ratio is more sensitive to change of fluid type than V_P or V_S separately. The use of V_P/V_S is a key parameter in reservoir study and it plays a key role especially for lithology and fluid type prediction methods. Well C produced gas from Abu Rawsh G formation and well D produced oil from Baharyia formation and Kharita is considered as water aquifer of the sandstone field under study.

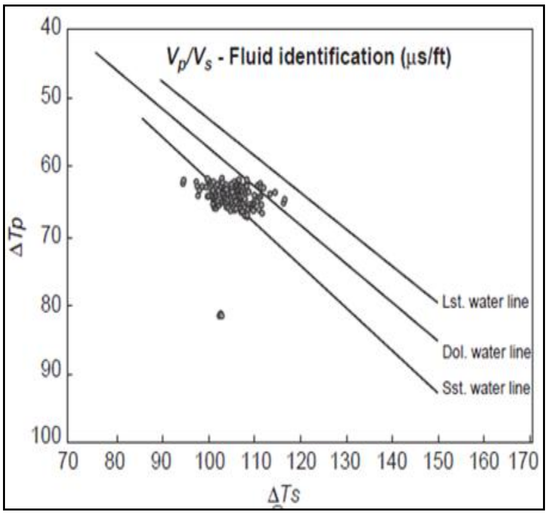


Figure 7 V_P/V_S cross-plot for Kharita formation, well C.

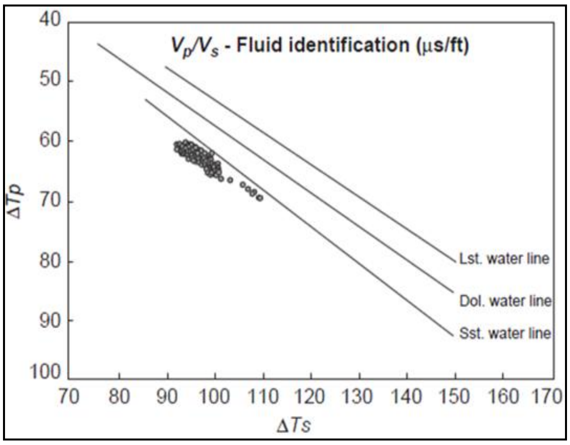


Figure 8 V_P/V_S cross-plot for Baharyia formation, well C.

CONCLUSIONS

- As the compaction pressure increases, the effect of grain size on porosity become less. Also, the compaction pressure factor can affect permeability more than the cementing material concentration factor could. For a small grain size, the effect of the grain size factor on the permeability was the main factor at all conditions even at high compaction pressure.

- Developed relations have shown that ultrasonic wave velocity increases with the decrease of porosity, cementation, mean pore sizes and compaction pressure.

- A relationship has been developed between sand permeability and ultrasonic wave velocity at different compaction pressures. This relation can help in determining rock permeability from measured physical property in additions to the published techniques such as resistivity, NMR and Ø-Swi.

- V_P/V_S cross-plot has proved as a good tool to identify type of saturating reservoir fluids; water, oil and gas. This technique presumes formations have similar lithology and same porosity.

- Results of well testing data for studied wells confirmed the conclusions of HCM factor and V_P/V_S cross-plot technique in testing hydrocarbon movability and in identifying reservoir fluids

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