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Reservoir Fluids Identification Using V_p/V_s Ratio

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Résumé — Identification de fluides de réservoir par le rapport V_p/V_s — Le temps de propagation des ondes sismiques de compression est largement utilisé pour la détermination de la porosité. En se servant à la fois des ondes sismiques transversales et des ondes de compression, il est possible de discriminer les propriétés mécaniques des roches. L'utilisation du rapport de vitesses des ondes sismiques de compression et transversales, V_p/V_s, permet de définir une méthode pour identifier la nature des fluides saturant les pores de la roche. Le rapport V_p/V_s varie selon le fluide (eau, huile et gaz) présent dans les pores de la roche. Des exemples tirés des études de champs montrent comment la représentation du rapport V_p/V_s sous forme graphique permet d'identifier la nature des fluides saturant les roches de réservoir.

Abstract* — *Reservoir Fluids Identification Using* V_p/V_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 is sensitive to the saturating fluid type. The use of the ratio of compressional wave velocity to shear wave velocity,* V_p/V_s, *is a good tool in identifying fluid type. The fact that compressional wave velocity decreases and shear wave velocity increases with the increase of light hydrocarbon saturation, makes the ratio of* V_p/V_s *more sensitive to change of fluid type than the use of* V_p or V_s *separately. Field examples are given to identify fluids type (water, oil and gas) using the* V_p/V_s *ratio. Field examples have shown that shear travel time decreases while compressional travel time increases when the water saturated points become gas or light oil saturated points in the studied sections. The decrease of shear travel time (increase of shear wave velocity) is due to the decrease of density and the absorption of deformation by free gas in pores. The increase of compressional travel time (decrease of compressional wave velocity) is due to the decrease of bulk modulus of reservoir rocks which compensates the decrease of rock density.*

NOMENCLATURE

V_p Compressional wave velocity
V_s Shear wave velocity
V_{pf} Compressional wave velocity for fluid
V_{pw} Compressional wave velocity for matrix
V_{sf} Shear wave velocity for fluid
V_{sw} Shear wave velocity for matrix
k Bulk modulus
μ Shear modulus
ρ Rock density
σ Poisson's ratio
E Young modulus
Δ_{Tp} Compressional wave transit time
Δ_{Ts} Shear wave transit time
Δ_{Tpf} Compressional wave transit time for fluid
Δ_{Tpm} Compressional wave transit time for matrix
Δ_{Tsf} Shear wave transit time for fluid
Δ_{Tsm} Shear wave transit time for matrix.

INTRODUCTION

In the acoustic sense, the properties which define the seismic wave velocity are the elasticity parameter, E and density, ρ. The basic equation is $v = (E/\rho)^{0.5}$, since the elementary observations tell us that dense rocks trend to have high velocity. This signifies that the effect of elasticity on velocity is much greater than the effect of density. We know that, there are several modulus of elasticity. To obtain the seismic velocity, we must select the appropriate modulus of elasticity. The three elastic modulus which concern us are young modules (E), bulk modulus (k) and rigidity modulus (μ). For P-wave, the appropriate value of E is $K + 4/3\ \mu$ or $\lambda + 2\mu$, while for S-wave the appropriate value of E is μ [1-4].

P-wave transit time data are very useful in identifying lithology, porosity and pore fluids. *S*-wave data are also useful for mineral identification and porosity determination. There is evidence that *S*-wave transit time may be useful for fluids identification. Combining *S*-wave data and *P*-wave data will help in fluid type identification especially gas reservoirs.

The use of *P*-wave and *S*-wave is very helpful in identifying fluids type in porous reservoir rocks. It is found that *P*-wave velocity decreases and *S*-wave velocity increases with the increase of light hydrocarbon in place of brine saturation. This is true within the range of free gas or free hydrocarbon saturation. In this paper, the technique of V_p/V_s is presented as fluid identification tool and field examples are presented to show how the V_p/V_s crossplot can distinguish between water, oil and gas saturated zones [5-7].

1 FACTORS AFFTECTING VELOCITY

The most important aspect in which rocks differ from homogeneous solids is in having 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.

The time average equation is often used to relate the velocity, V and porosity, φ, known as Wyllie equation; it assumes the travel time per unit path length in fluid filled porous rock is the average of the travel times per unit path length in the matrix $1/V_m$ and in the fluid $1/V_f$:

$$1/V = \phi/V_f + 1 - \phi/V_m \tag{1}$$

where:
V seismic wave velocity
V_f fluid velocity
ϕ effective formation porosity.

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 [8, 9].

1.1 Type of Seismic Waves

In the previous section, we summarized factors affecting the velocity of compressional and shear waves, generally referred as body waves. In the following section we shall describe the characteristics of such waves [10].

1.1.1 Compressional Waves, 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 motion of the particles is always in the direction of wave propagation. The distance between two rarefactions or condensation is known as wavelength or period.

The relation between compressional velocity V_p and density (ρ) and elastic constants can be expressed as following:

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

where:
V_p compressional wave velocity;
E Young modulus;
σ Poisson ratio;
λ Lame's constant;
μ rigidity modulus;
ρ rock density.

1.1.2 Shear Waves, 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 of other constants, as indicated by the relation.

$$V_s = (\mu/\rho)^{0.5} \quad (3)$$

$$= [(E/\rho)\,(1/2(1+\sigma)]^{0.5} \quad (4)$$

where:

V_s shear velocity;
E Young modulus;
σ Poisson ratio;
μ rigidity modulus;
ρ rock density.

1.2 V_p/V_s Combination

Comparing *P*-wave velocity and shear wave velocity equations, we see that the ratio between compressional to shear wave velocity is:

$$V_p/V_s = [\,(\lambda + 2\mu)/\mu]^{0.5} = [(k + 4/3\mu)/\mu]^{0.5} = [(1-\sigma)/(0.5-\sigma)]^{0.5} \quad (5)$$

where k is the bulk modulus of rock. Values of Poisson ratio σ vary from 0.0 to 1.0

Either expression tells us that the compressional velocity will always be greater than the shear velocity in a given 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. As shear deformation cannot be sustained in liquid ($\mu = 0$) shear waves will not propagate in liquid material at all. Otherwise, Equations (3-5) show that V_r is greater than V_s in given medium. Both radicals must be greater than one, the first because k and μ are always positive, the second because σ cannot be greater than 0.5 in an ideal solid [11-14].

From velocity equations, it is clear that shear wave velocity is more affected by rigidity modulus than compressional wave velocity.

Equation (1) can take the following form for *P*-wave:

$$1/V_p = \Phi/V_{pf} + 1 - \Phi/V_{pm} \quad (6)$$

or:

$$\Delta_{Tp} = \Delta_{Tpf}\phi + (1-\phi)\,\Delta_{Tpm} \quad (7)$$

and for shear wave the form:

$$1/V_s = \Phi/V_{sf} + 1 - \Phi/V_{sm} \quad (8)$$

or:

$$\Delta_{Ts} = \Delta_{Ts}\phi + (1-\phi)\,\Delta_{Tsm} \quad (9)$$

where Δ_{Tp} is *P*-wave transit time and Δ_{Ts} is *S*-wave transit time.

Seismic velocity (V_p or V_s) in the Equations (6-9) 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.

Equations (7) or (9) can be solved for porosity with assumption of known fluid velocity and matrix velocity. In hydrocarbon reservoir such derived porosity needs hydrocarbon correction. In gas reservoir it is recommended to use density log rather than sonic to get porosity.

2 V_p/V_s CROSSPLOT – FLUID IDENTIFICATION

Equations (6-9) can be solved for fluid velocity instead of formation porosity with the assumption of known porosity and matrix velocity. *P*-wave velocity in water is greater than that in oil and in gas. Consequently recorded *P*-wave velocity is sensitive to fluid change from water to oil or gas. From velocity Equations (2) and (3), it is clear that shear velocity is more sensitive than *P*-wave to fluid type. This sensitivity difference is attributed to the fact that *S*-wave depends mainly on rigidity modulus, μ parameter while V_p depends on λ and μ parameters. Combining shear wave and compressional wave velocities will give new parameter V_p/V_s. This parameter is more sensitive to fluid nature than *P*-wave or *S*-wave alone.

Following Table 1 resumes travel time ΔT for *S*-wave and *P*-wave in most reservoir rocks. V_p/V_s crossplot is constructed using these matrix constants in µs/m.

TABLE 1

Shear and compressional waves travel time (µs/m)

Rock type	Δ_{Tp}	Δ_{Ts}
Limestone	142.5	270
Dolomite	130.5	238
Sandstone	159	258
Water	567	1050

The use of shear wave together with the compressional wave may be very useful for fluid identification. 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 conjugately 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. The ease with which the solid material can deform into pore is scarcely affected by the presence of some water; 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 also 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.

The use of V_p/V_s crossplot to identify fluid type is based on the fact that shear wave is more sensitive than P-wave to fluid change, consequently, V_p/V_s might be more sensitive to fluid change than either V_p or V_s. $\Delta_{Tp} - \Delta_{Ts}$ crossplot is preferred rather than the form of V_p/V_s crossplot. It is technically easier; values are taken directly from records to the crossplot. Figure 1 is V_p/V_s in µs/m. The three lines are limestone water base line, dolomite water base line and sandstone water base line. For a specific case, *e.g.* sandstone line, points lie on the sandstone line or above (in case of $\rho_f > 1$ g/cc) are water points, the point lie below sandstone line are oil points or gas points. Light hydrocarbon or gas will cause a decrease in shear travel time and an increase in compressional travel time with respect to water point. This will shift the water point to south west corner of the crossplot, defined as gas arrow effect in the crossplot. Gas points will show more departure from sandstone water base line than oil points and more shifted to the left of greater shear travel times. This technique can be applied for limestone or dolomite reservoir rocks. The use of V_p/V_s crossplot can be useful for fluid identification for given reservoir rock (same porosity and same matrix) especially in gas reservoir [15-20].

3 FIELD EXAMPLES

Following are certain examples of V_p/V_s application as fluid identification tool in three fields, Western Desert, Egypt. All seismic data for shear and compressional waves have acquired by AST (array sonic tool) seismic survey.

3.1 Field Example 1

Producing well has been tested to shows fluid nature of different sections. Figure 2 shows V_p/V_s crossplot for Unit 5 in D18 in a gas producing well, Western Desert, Egypt. This unit is a gas producing unit. The points shown in Figure 3 indicate very clearly that it is a gas zone. Figure 3 is the V_p/V_s crossplot for Unit 5 in JB173. This Unit 5 in JB173 produces water. The V_p/V_s crossplot points shown in Figure 3 indicate that the unit is water.

3.2 Field Example 2

Field example 2 shows a well having two units; Unit 2 and Unit 3-1 is gas and Unit 3-2 is water. Figure 4 is the V_p/V_s

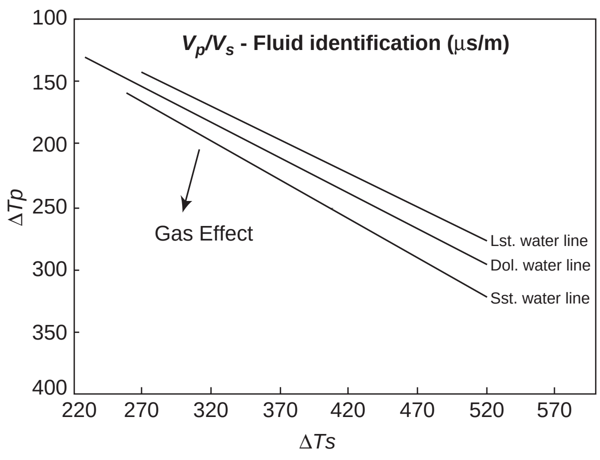

Figure 1

V_p/V_s crossplot - Fluid identification.

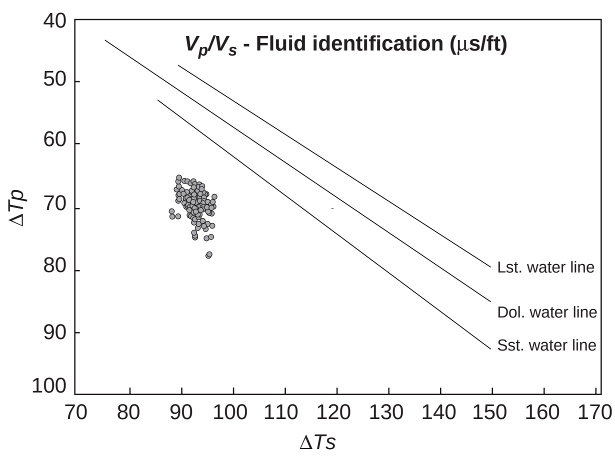

Figure 2

V_p/V_s crossplot for gas zone in D18, Western Desert, Egypt.

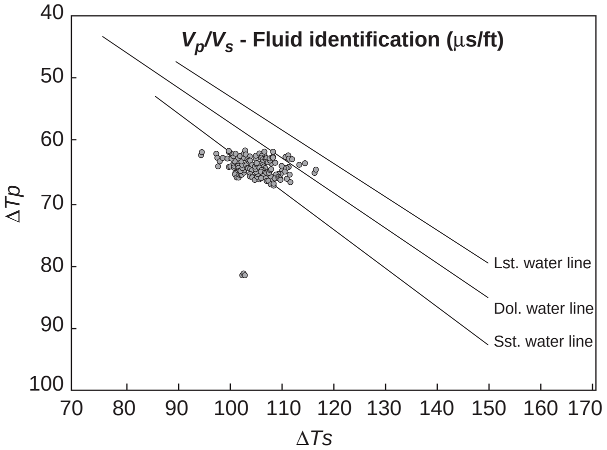

Figure 3

V_p/V_s crossplot for water zone in sand Unit 5, Western Desert, Egypt.

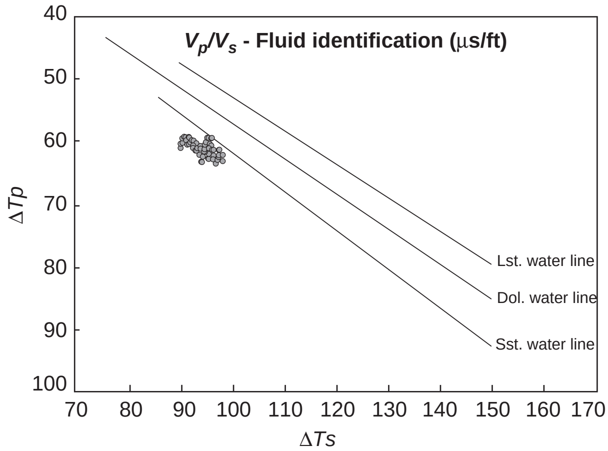

Figure 4

V_p/V_s Crossplot for gas zone, Unit 2, Western Desert, Egypt.

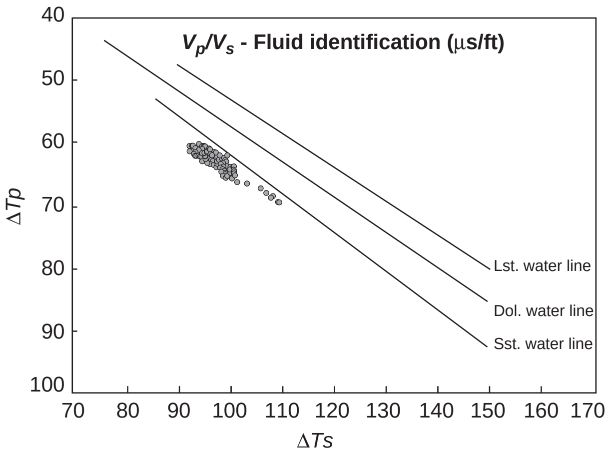

Figure 5

V_p/V_s Crossplot for water zone, Unit 3-2, Western Desert, Egypt.

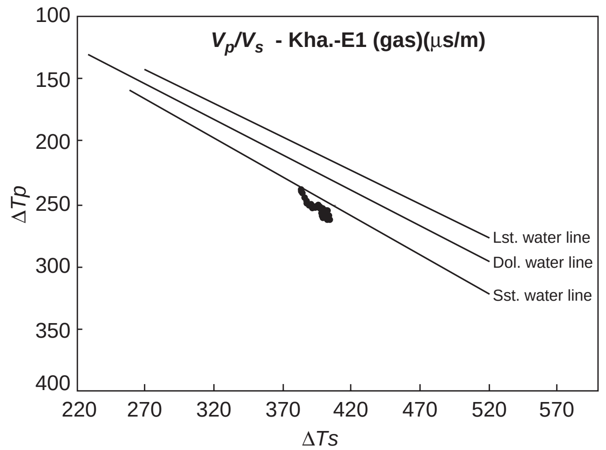

Figure 6

V_p/V_s crossplot for gas zone Kharita formation, Western Desert, Egypt.

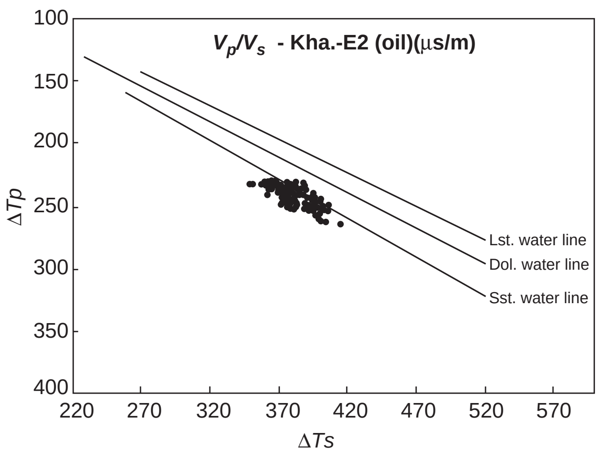

Figure 7

V_p/V_s crossplot for oil zone, Kharita formation, Western Desert, Egypt.

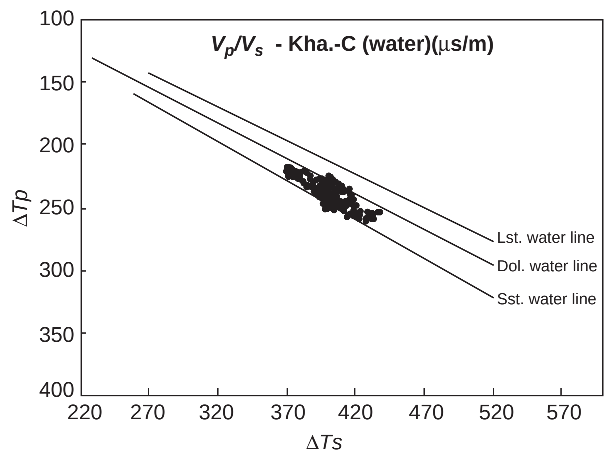

Figure 8

V_p/V_s crossplot for water zone Baharia formation, Western Desert, Egypt.

crossplot for Unit 2; the points have fallen below the water line and shifted to the left, which shows gas zone. Figure 5 contains the points for Unit 3-2 which is water zone. The points shown in the figure are shifted to the right and close to water line. This indicates that the unit is water.

3.3 Field Example 3

V_p/V_s crossplot has been applied in a well producing from four sections in Kharita formation, Western Desert, Egypt. Figure 6 is the V_p/V_s crossplot in Kharita, E1, JG2 which is gas producing. The points have lied below the line, this indicates a gas zone. Figure 7 is the V_p/V_s cross plot for oil section, the points lie also below the line but is shifted with respect to the gas section points. This shift due the effect of oil on shear wave is different from the effect of gas on shear wave velocity. Figure 8 is V_p/V_s crossplot in water section Bahariya formation, Western Desert.

CONCLUSION

V_p/V_s crsossplot is a good tool to identify fluid nature for the same formation. It has been tested in several field examples with different fluid types (oil, gas and water).

This technique assumed that the same has the same porosity and it has the same lithology.

It is recommended to introduce it as an additional tool in identifying fluid nature of new sections.

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