International Journal of Petroleum and Geoscience Engineering (IJPGE) 2 (4): 350-360, 2014
ISSN 2289-4713

Research paper

Investigation of Fluid Movement Effect on Seismic TWT in Carbonate Reservoirs

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A b s t r a c t

4D seismic has evolved from a qualitative tool to identify producing zones and bypassed oil, to become an integral part of quantitative reservoir management. Therefore, the 4D seismic is commonly expensive, feasibility study must be done on each region and/or field to examine whether the rock properties and fluid parameters let using seismic methods for reservoir monitoring or not. In this study which is done on a part of carbonate formation in southern Iran, using Kuster-Toksoz equations and Gassmann's, seismic parameters variations due to changing fluid saturation in a well of carbonate oil reservoir, are calculated. Then by using of Aki-Richard equation, synthetic seismograms for before and after oil production are generated. Consequently, time lapse seismic method could be accomplished on this oil field.

Keywords:

Reservoir monitoring, Rock physics, Kuster-Toksoz, Carbonate rocks.

Accepted: 30 November2014

1. Introduction

4D seismic is designed for investigation of changes in reservoir conditions (saturation, pressure, temperature and sometimes porosity) resulted from production or injection, using seismic data. There are two interconnected stages in using this method. One of them is the rock physics which relates reservoir conditions and other reservoir properties to the elastic and non-elastic properties of reservoir and consequentially to the velocity and attenuation [1]. The second stage is the selection of seismic attributes that are very sensitive to the dependency of velocity and attenuation relative to reservoir conditions change. For instance when oil is replaced by water in oil zones, the p-wave velocity increases and the s- wave velocity decreases in rocks is not too stiff. Based on this fact, the decrease in travel time to reservoir bottom interface reflection can cause a pull up on seismic-time section P-P. Because the decrease in S wave velocity relative to that of P wave is too low on p-s section, a pull down will be small. In addition a change velocity resulted from fluids movements in reservoir, the decrease in the amplitude of reflection waves in the top and base of the reservoir can be seen which can be greater in far offset. Moreover, changes in effective pressure and fluid viscosity may result in enough change in attenuation for the change in the amplitude spectrum on the bottom reflection event to be seen.

The most important issue prior to performing 4D seismic for visualization and interpretation of the changes occurred in the reservoir throughout production and time, is knowing the fact that whether these changes can be visualized in seismic data or not. Therefore, initially the amount of seismic data changes due to reservoir conditions changes should be calculated using low cost and fast methods, and the visualization possibility of reservoir changes due to production in seismic data should also be evaluated [2].

2. Rock Physics Models

The operation costs of seismic data acquisition and processing are high and with respect to the reservoir conditions (reservoir rock properties and pore fluid properties, production conditions, changes in fluids, temperature and pressure of the reservoir) and variations applied in them as a result of fluid production and fluid substitution, on the other hand, the seismic data resolution may not exhibit these variations. Therefore, prior to performing a new seismography, in order to investigate the reservoir changes, it is necessary to calculate the amount of changes in seismic parameters as a result of hydrocarbon production using the available and low cost theories and models and one should investigate the possibility of viewing these changes in the seismic data and in case the results are promising, one should move into the execution stage of new data acquisition. Gasmann and Kuster-Toksoz [3] equations are among the important and practical models in this context. First we will briefly introduce these two equations and then will discuss the changes of synthetic seismogram for carbonate reservoirs with two fluids and the effect of fluid movement on the two way travel time of the wave and amplitude using Aki and Richards equation. Carbonate sediments are prone to rapid and pervasive diagenetic alterations that change the mineralogy and pore structure within carbonate rocks [4]. Especially the cementing and dissolution processes continuously modify the pore structure to create or destroy porosity. In the extreme cases, these alterations can completely turn the mineralogy from aragonite/calcite into dolomite, or can invert the pore distribution of the rocks. This means the main granulations are dissolved and make porosity and constitute the main cemented spaces [4].

All of these alterations change the elastic properties of rock and consequentially the velocity of sound waves in it. The result of these phenomena is the increase in the extension of the changes of the sound waves in carbonate rocks, so that in these rocks, the velocity of p-wave and s- wave varies between 1700 to 6000 m/s and between 600 to 3500 m/s respectively [4].

The main controlling factor of velocity in rocks is porosity [5], [6]. The most of available theoretic equations ignore the changes in the elastic properties caused by the type of pore spaces. As a result, the quantitative results obtained from seismic inversion, AVO and the calculation of the pores volume that are based on these equations, are subject to high uncertainties.

Carbonate rocks have complicated pore system including interparticle and intercrystalline, microporosity, moldic porosity, interframe porosity and etc. on the other hand, the results of new research exhibits that seismic velocity and also the relation between the velocity and porosity are intensely influenced by the type of the pores in rock. Therefore, the validity of Gasmann equation in carbonate rocks is unknown and the development of a rock physics model for these rock types is very difficult. Empirical rock physics models are vastly used in the industry because of ease in their use. These models typically suppose a linear relation between porosity and seismic velocity and often find a good relation between one physical property like permeability and the velocity of waves and in this case, permeability is considered to be an important parameter in controlling the velocity while the velocity is intensely controlled by porosity. It can be said that the empirical relationships can take into account a very limited number (usually less than three parameters) of parameters affecting the velocity of seismic wave travel within rock.

Inclusion-based models like Custer-Toksoz [3] can comprise a few factors and effective parameters such as porosity, mineralogy, pore and fluid type. Typically these models are first order because they ignore the interaction between the pores and are valid for the cases with thin fluid. Since the shape of pores greatly affects the elastic modules and the velocity of waves as a result, and Gasmann equation does not independently take into account these parameters, we used Custer-Toksoz model for modeling the changes of seismic p-waves velocity resulted from the reservoir fluid change.

3. Gasmann Equation

If the fluid is equilibrated throughout the rock deformation process, the bulk module of saturated rock can be obtained from the bulk module of the dry rock as follows:

$$K = K_d + \frac{\left(1-\frac{K_d}{K_s}\right)^2}{\frac{\emptyset}{K_f}+\frac{1-\emptyset}{K_s}+\frac{K_d}{{K_s}^2}} \tag{1}$$

Where K, K_d, K_f and K_s are the bulk modules of saturated rock, dry rock, fluid and solid rock respectively and φ is the porosity. Equation 1 is known as Gasmann equation [17]. Gasmann model assumes that the fluid is in equilibrium and this occurs when the seismic frequency is low enough and the local and overall fluid flow can equilibrate the pressure distribution within all of the fluid phases. This model is known as low frequency or zero frequency. Note that when using this model, K_f is the effective bulk module of the mixed fluid of the pore. In the condition of fluid pressure equilibrium, K_f can be calculated by harmonic average relation.

4. Kuster-Toksoz Equations

Models presented in articles and books about elastic and non-elastic properties of the rock, show that the geometry of the pores (voids) is as an important factor affecting seismic data. That's why many researchers including, [3], [7-19], have been studied the effects of pore geometry on seismic parameters.

Among these models, Kuster-Toksoz models (KT) based on scattering theory is one of the most realistic and simplified models that often used by geophysicist. Then in this paper after briefly introduced of those equations, are used to estimate the type and percentage of pores in reservoir. When type and percentage of pores were identified by using of inverse modeling of Kuster-Toksoz Equations, elastic properties of reservoir (such as bulk and shear modulus p wave velocity and …) and p wave two way travel time, after fluid substitutions, are calculated, and finally by the using Aki Richards equation, synthetic seismogram was created.

The model presented by Custer-Toksoz for calculating elastic modules based upon the shape of the pores in rock, is as follows:

$$(K_{KT}^* - K_m)\frac{\left(K_m+\frac{4}{3}\mu_m\right)}{\left(K_{KT}^*+\frac{4}{3}\mu_m\right)} = \sum_{i=1}^{N} x_i\ (K_i - K_m)P^{mi} \tag{2}$$

$$\left(\mu_{KT}^* - \mu_m\right)\frac{(\mu_m+\zeta_m)}{(\mu_{KT}^*+\zeta_m)} = \sum_{i=1}^{N} x_i\ \left(\mu_i - \mu_m\right)Q^{mi} \tag{3}$$

In equation 2 and 3, K_{KT}^* and μ_{KT}^* effective elastic modules based upon the shape of the pores, K_m and μ_m elastic modules of rock matrix K_i the bulk module of the i^th^ fluid in the pores

$$\zeta = \frac{\mu}{6}\frac{(9K+8\mu)}{(K+2\mu)} \tag{4}$$

P^{mi} and Q^{mi} coefficients show the effect of the i^{th} fluid in pore space m and are tabulated in Table. 1.

Table. 1: P and Q coefficients for special shapes. Subscripts i , m denote the fluid inside the rock and its matrix respectively.

Inclusion Shape	P^{mi}	Q^{mi}
Spheres	$\frac{K_m+\frac{4}{3}\mu_m}{K_i+\frac{4}{3}}$	$\frac{K_m+\frac{4}{3}\mu_m}{K_i+\frac{4}{3}\mu_m}\frac{\mu_m+\zeta_m}{\mu_i+\zeta_m}$
Needles	$\frac{K_m+\mu_m+\frac{1}{3}\mu_i}{K_i+\mu_m+\frac{1}{3}\mu_i}$	$\frac{1}{5}\left\{\frac{4\mu_m}{\mu_m+\mu_i}+2\frac{\mu_m+\gamma_m}{\mu_i+\gamma_m}+\frac{K_m+\frac{4}{3}\mu_m}{K_i+\mu_m+\frac{1}{3}\mu_i}\right\}$
Disks	$\frac{K_m+\frac{4}{3}\mu_i}{K_i+\frac{4}{3}\mu_i}$	$\frac{\mu_m+\zeta_i}{\mu_i+\zeta_i}$
Penny Cracks	$\frac{K_m+\frac{4}{3}\mu_i}{K_i+\frac{4}{3}\mu_i+\pi\alpha\beta_m}$	$\frac{1}{5}\left\{1+\frac{8\mu_m}{4\mu_i+\pi\alpha(\mu_m+2\beta_m)}+2\frac{K_i+\frac{2}{3}(\mu_m+\mu_i)}{K_i+\frac{4}{3}\mu_i+\pi\alpha\beta_m}\right\}$

$$\beta=\mu\frac{(3K+\mu)}{(3K+4\mu)}\quad \gamma=\mu\frac{(3K+\mu)}{(3K+\mu)}\quad \gamma=\frac{\mu}{6}\frac{(9K+8\mu)}{(K+2\mu)}$$

5. Methodology

Based on the petrophysical evaluations performed, the reservoir under study is principally composed of lime dolomites, dolomite limes and pure lime and has a good porosity between 11 and 15 percent. The shape of pores is among important and effective factors on seismic parameters specifically in carbonate rocks. Varied techniques such as thin section study and CT scan are employed in this respect. Although these techniques are precise and the study is performed on that reservoir's samples but it is punctual and comprises few points. Therefore in this study, firstly the shape and percent of the pores were calculated using inverse modeling of Custer-Toksoz [20]. Then with the fluid change, bulk and shear modules and density of reservoir were calculated and P and S wave velocities in the reservoir after fluid substitution were calculated using the relations between bulk and shear modules and P and S wave velocities. Eventually, once the density plot and the P- wave velocity were calculated using the changed fluid, the synthetic seismic section was prepared. In the reservoir under study, the reservoir gas is being injected for enhanced oil recovery.

The initial data used in this study, is porosity, acoustic and density logs (blue lines in figure 1). Using this data and the available rock physics relations, the p-wave and s-wave velocity logs, p- and s- wave modules in oil saturated and dry states and p- and s- wave modules of rock matrix were calculated. The required fluid parameters in different depths are presented in table 2.

Table. 2: Parameters of reservoir fluid in different depths.

Sample depth (ft.s.s)	**Reservoir pressure (Psi)**	**Temp. (°F)**	**Saturation pressure (Psi)**	**GOR (SCF/STB)**	**Bulk module (Gpa)**	**Bo (bbl/Stb)**	**Fluid density (gr/cc)**
9411	5461	200	5100	1527	0.55	1.8492	.8665
10536	5672	205	4963	1490	0.44	1.8222	.8633

The different stages of the approach are as follow:

1. The determination of elastic properties (in reservoir temperature and pressure) of the fluid including un-situ oil, reservoir water and the injected fluid (gas).

2. The determination of elastic properties of reservoir rock in initial conditions (saturated in oil) and reservoir rock matrix (using well logs and the referenced books and papers).

3. Modeling the type and the percentage of reservoir rock pore spaces using Kuster and Toksoz relationships [20].

4. The calculation of changes in elastic properties of reservoir rock caused by fluid change using Kuster and Toksoz relationships.

5. The calculation of changes in elastic properties of reservoir rock caused by fluid change using Gasmann relationship.

6. Generate Synthetic seismogram in new reservoir condition

Table 3 shows the average change in elastic properties due to fluid substitution that computed by Gasmann and Kuster & \Toksoz equations. In this table, the difference in result is due to the shape of the pores that are not considered in Gasmann equation.

Table. 3: average change in elastic propety due to fluid substitution

Method	**Change in V_p**		**Change in K**		**Change in density**		**Change in V_s**	
	Km/sec	%	GPa	Km/sec	%	%	Km/sec	%
Kuster & Toksoz	-0.38812	7.826038	-2.60071	8.28822	-0.07892	3.428196	0.063668	1.759956
Gasmann	-0.163	3.2	-1.35	4.3	-	-	-	-

Fig. 1 (a and b) demonstrate the plots of p-wave velocity and density before and after gas injection respectively. These figures clearly demonstrate the effect of reservoir fluid on these plots. Since no fluid movement has happened at the bottom of the reservoir, the values of these parameters (velocity and density) have not changed and their plots have precisely overlapped. The changes in acoustic impedance versus fluid change are shown in Fig. 2. Since this parameter is the product of velocity time's density, the trend of its changes is proportional to the trend of velocity and density changes. Fig. 3.a depicts the seismic section of the reservoir before production (initial conditions) and Fig. 3.b shows the seismic section of the reservoir after production and the substitution of oil by gas.

As can be seen from the comparison of these two figures, when the oil is substituted by gas the two-way travel time of the wave becomes more and the reflector of the reservoir's bottom is seen deeper. In this reflector, the time of 420 ms has increased close to 447 ms. the vertical movement seen in the reservoir's bottom reflector, is approximately 27 ms that is caused by the p-wave velocity reduction in the reservoir due to the oil substitution by gas. In addition to the change in the two-way travel time of the wave, the fluid change causes change in the amplitude specifically in high offsets which can be seen in these figures.

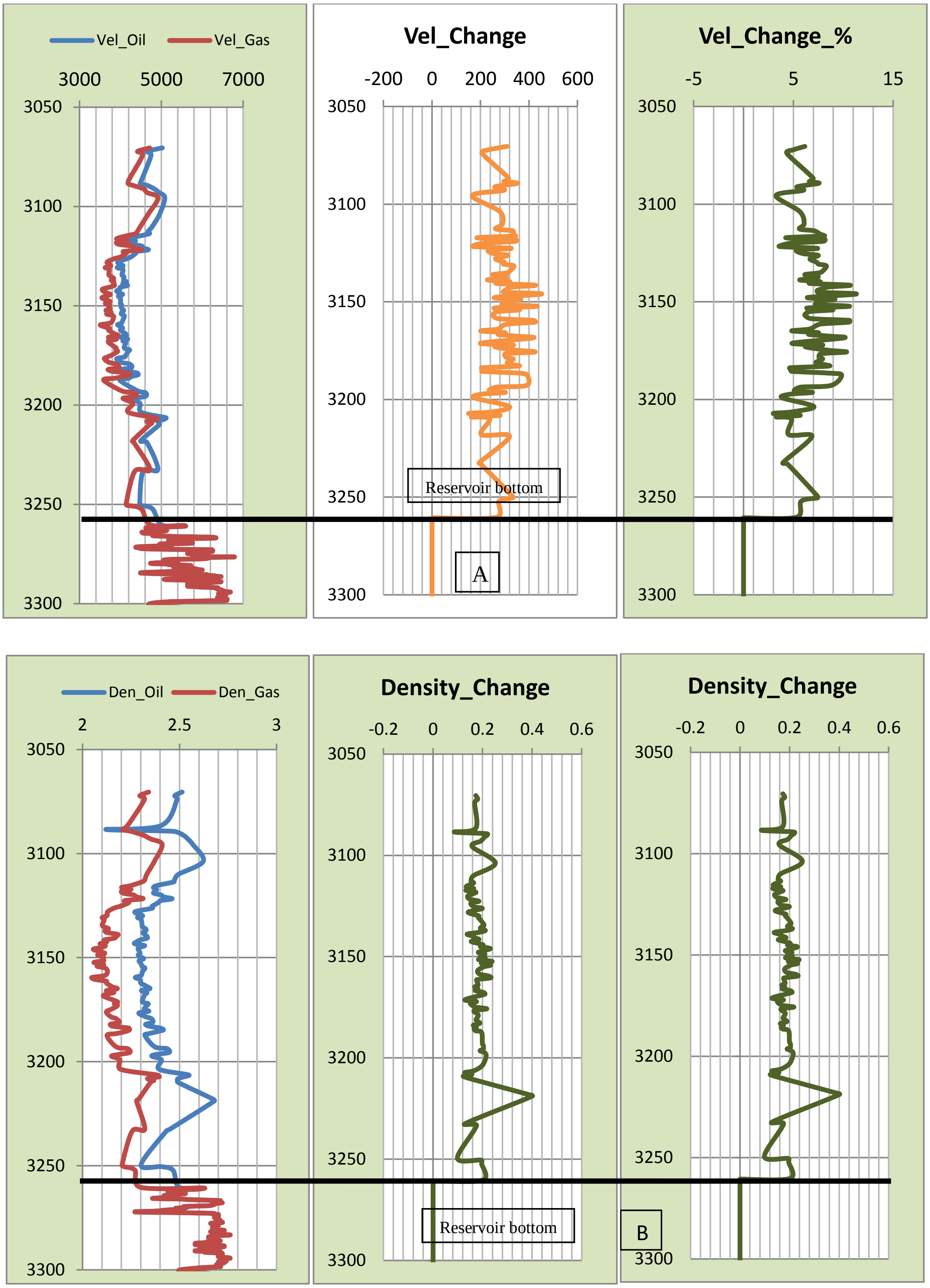

Fig. 1: The comparison of p-wave velocity in ms (fig. 1.a) and rock density (fig. 1.b) of the reservoir versus fluid movement. The blue line shows the parameters' values (velocity and density) in the oil-saturated state (input data) and the red line shows the parameters' values in the gas-saturated state. The vertical axis is in meters.

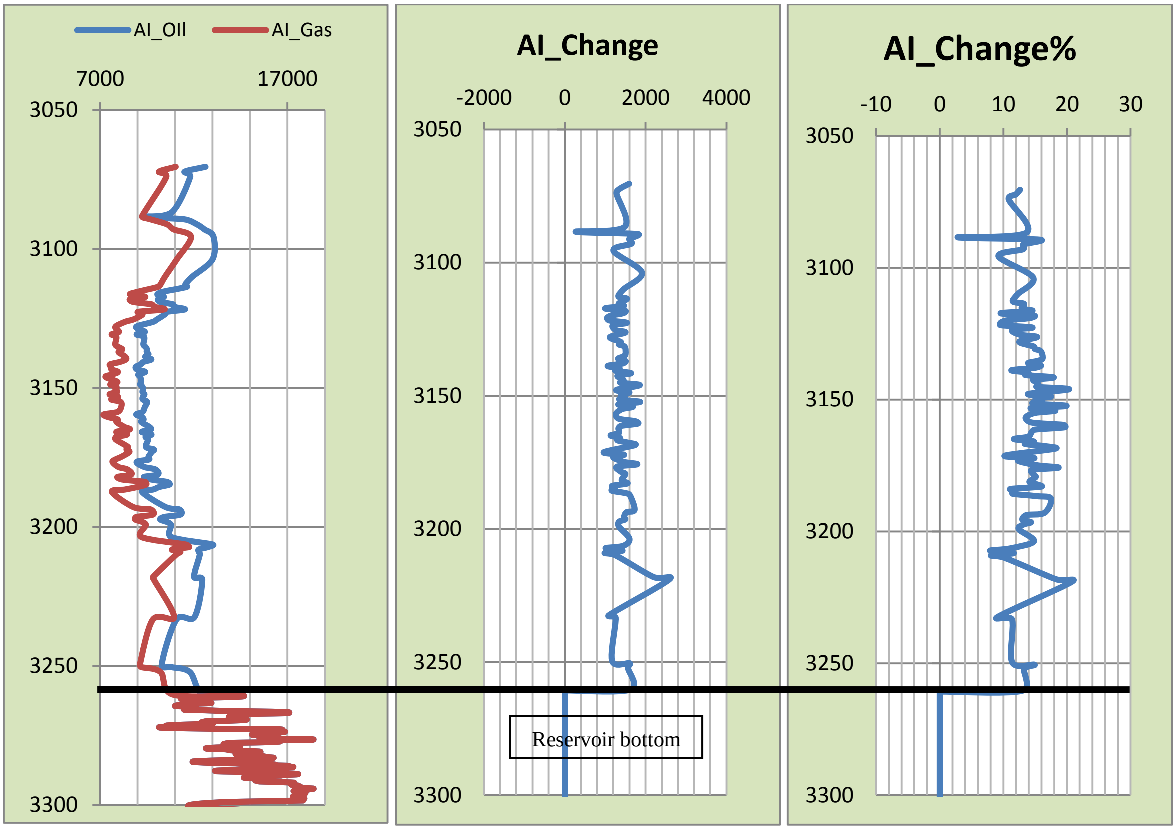

Fig. 2: The comparison of the reservoir's acoustic impedance in the oil-saturated state (blue line) or the reservoir's acoustic impedance in the gas-saturated state (red line). The vertical axis is in meters.

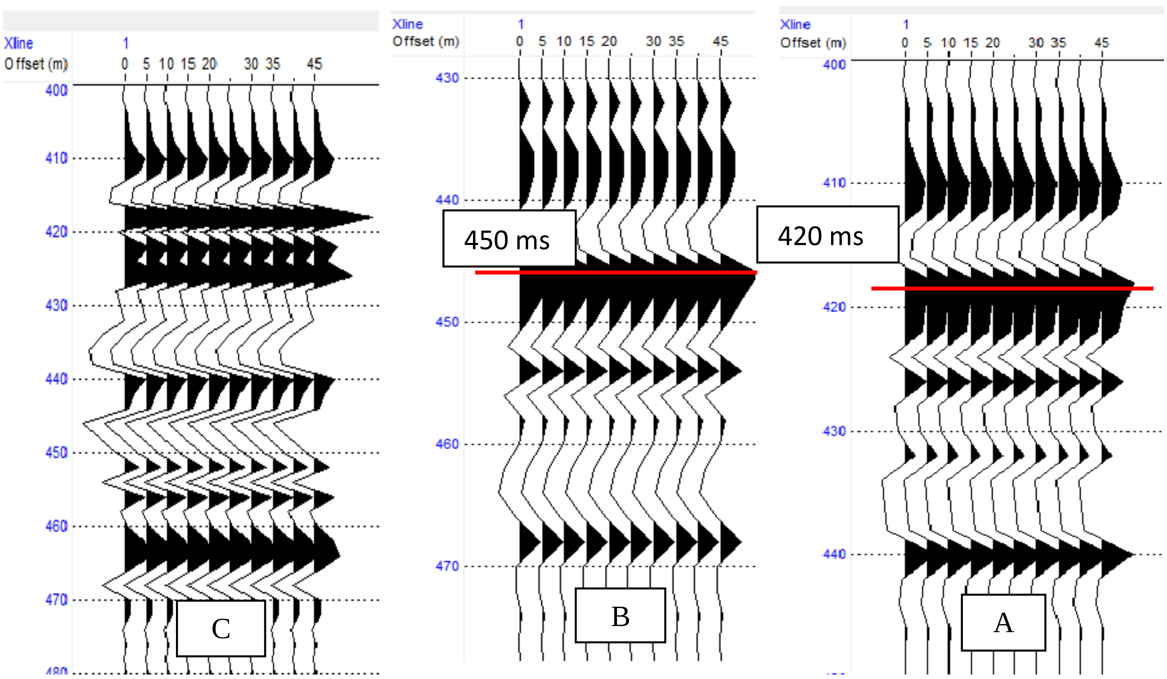

Fig. 3: Time seismic section (3.a) before, (3.b) after gas injection for oil production (3.c) their difference.

Fig. 4 exhibits the difference in the seismic section formed followed by gas injection for oil production.

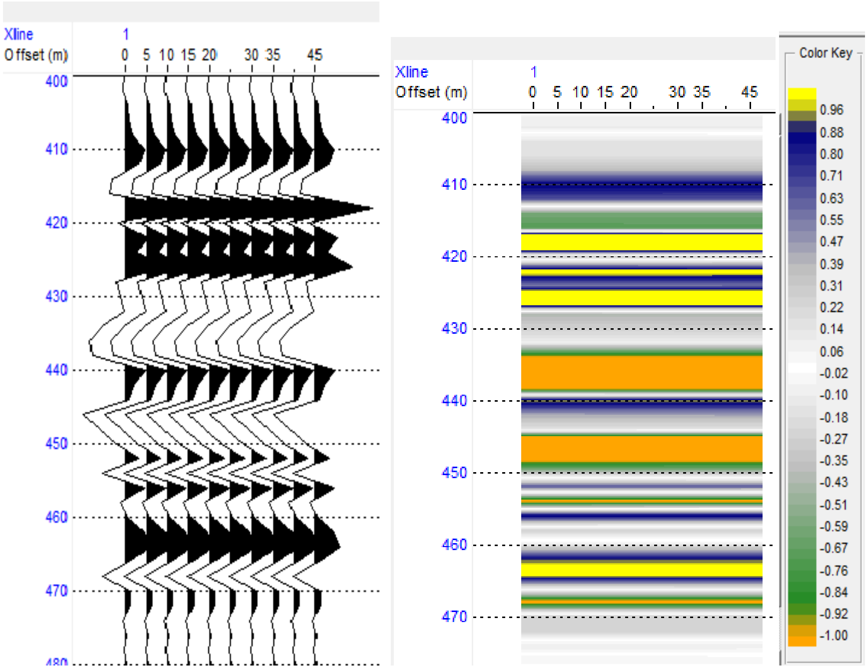

Fig. 4: The difference formed in the seismic section after gas injection for oil production.

These figures show that the changes in the carbonate reservoir caused by gas injection for oil production are visible and pursuable by seismic data and one can see the reservoir's new conditions using new survey, processing and interpretation. Then one can explore the areas of the reservoir that have not had any production yet, and can plan for their production afterwards.

4. Conclusions

This study shows when the oil is substituted by gas the reflector of the reservoir's bottom is seen deeper and the vertical movement seen in the reservoir's bottom reflector, is approximately 27 ms that is caused by the p-wave velocity reduction in the reservoir due to the oil substitution by gas. In addition to the change in the two-way travel time of the wave, the fluid change causes change in the amplitude specifically in high offsets. These results show that the changes in elastic properties of this carbonate reservoir caused by gas injection for oil production are visible and pursuable by seismic data and one can see the reservoir's new conditions using 4D seismic.

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