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VELOCITIES OF COMPRESSIONAL AND SHEAR WAVES IN LIMESTONES AND DOLOMITES IN A GAS FIELD OF SW IRAN

SEYYED ALI FA'AL RASTEGAR[1] and ABDOLRAHIM JAVAHERIAN[2*]

[1] Department of Petroleum Engineering, Amirkabir University of Technology, Tehran, Iran.
[2] Institute of Geophysics, University of Tehran, Tehran, Iran.
[*] Present address: Department of Petroleum Engineering, Amirkabir University of Technology, Tehran, Iran.
saf.rastegar@aut.ac.ir, javaheri@ut.ac.ir

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ABSTRACT

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Carbonates are the second important lithologies, after silicates, in petroleum reserves. Using three wells and DSI tools in one of the gas reservoirs in the Persian Gulf, Iran, four equations between compressional and shear wave velocities have been determined for limestones and dolomites. Then, these relationships have been compared with Castagna's relationships. It is concluded that Castagna's relationships estimated for V_S are less than the actual values in limestones and dolomites in the area of study. Using different crossplots, the gas and dolomitization effects on seismic velocities are studied. Consequently, understanding the gas and dolomitization effects make it possible to separate gas-saturated zones from water-saturated, and dolomites from limestones.

KEY WORDS: compressional velocity, shear velocity, correlation relationship, gas effect,
Poisson's ratio, dolomitization.

INTRODUCTION

Although dipole shear sonic images (DSI) logs are commonly acquired in wells, only monopole logs are available for many fields and wells and it is necessary to derive shear wave velocity (V_S) from the available compressional wave velocity (V_P). Among theoretical studies, laboratory measurements, statis-

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tical and empirical correlations that are used to find the relationship between V_P and V_S, the last seems to be the best (Wang, 2000). On the other hand, while many studies in silicate rocks, carbonate rocks have received insufficient attention (Verwer et al., 2008). Furthermore, the reported velocity data for dolomites cover only a limited range. There are empirical equations such as Han et al. (1986) and Castagna et al. (1993) to predict V_S from density and V_P logs, but these relationships are exact only in similar formations. Furthermore, Castagna et al. (1993) reported the velocity data for dolomites only over limited ranges. In this study, the relationships between V_P and V_S in limestones and dolomites are determined using DSI tools.

The ratio of V_P/V_S or, equivalently, Poisson's ratio is the relationship from which lithology is identified (Pickett, 1963; Nations, 1974; Kithas, 1976; Benzing, 1978; Tatham, 1982; Domenico, 1984; Rafavich et al., 1984; Pardus et al., 1990). Usually, V_P/V_S values, for fairly wide ranges of porosities, are 1.9 for limestones, 1.8 for dolomites, and 1.6 to 1.7 for sandstones. It is noted that mixed lithologies and the presence of gas make this identification difficult (Kithas, 1976). When the lithology is known, gas can be detected utilizing the velocity ratio (Kithas, 1976; Tatham and Stoffa, 1976; Tatham, 1982; Ensley, 1985). The presence of gas changes the usual relationship between V_P and V_S for the particular lithology. The behavior of carbonate rocks due to gas saturation is similar to that of sandstones. Namely, P-wave velocity and V_P/V_S ratio decrease (Li et al., 2003). These variations can be used as a sign of gas in the porous media. In the section on the effect of gas on V_P and V_S, dolomitization effects on V_P/V_S via different crossplots are shown.

THE AREA OF STUDY

The site of this study is one of the gas reservoirs in the Persian Gulf, Iran. Reservoir intervals in this field include the Bangestan and Khami groups, which have considerable amounts of gas. The main objective of drilling exploration and productive wells has been to access the Permo-Triassic Kangan and Dalan Formations (Afrassiabian and Najjarian, 2010). The Kangan and Dalan Formations have been divided into six members: Upper Kangan, K1, K2, K3, K4, and Nar. The Upper Kangan includes dolomites and anhydrites and has poor reservoir quality. The K1 member is an aging upper Triassic field with various lithologies including dolomite, limestone, and anhydrite layers. According to these reservoir characteristics, this unit is divided into three zones. Considering lithology, the K2 member is similar to the K1, but it is divided into two zones. The K3 is the upper part of the Dalan Formation and, in addition to dolomite and limestone, it also has anhydrite layers. The K4 and K3 are both divided into four zones. The K4 has no anhydrites and consists solely of dolomites and limestones. Last, the Nar member with anhydrite lithology has no reservoir property. Fig. 1 shows all reservoir formations in this field.

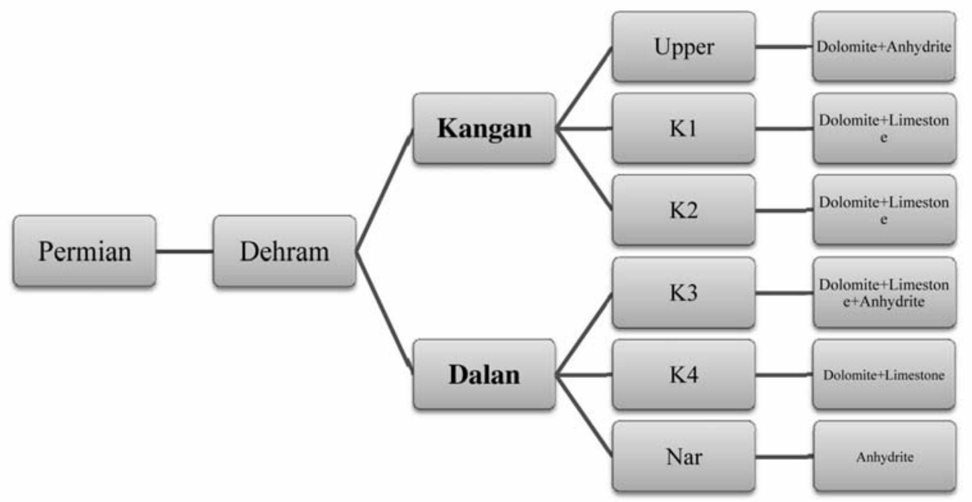


Fig. 1. Reservoir formations in the field of study (Afrassiabian and Najjarian, 2010).

Well data

Three wells with DSI, lithology and density logs were used in this study. V_P and V_S were extracted using DSI. The location of these wells with respect to each other is represented in Fig. 2. In these three wells, gas is usually produced through the regions which are without anhydrites.

RELATIONSHIPS BETWEEN V_P AND V_S

In general, empirical relationships between V_P and V_S are locally valid, so the best practice is to do local calibration and determine first or second order equations. In this paper, the regions with similar lithology (dolomite or calcite) were selected and the information of their V_P and V_S were calculated. Based on their saturating fluid, these regions were divided into two sections of water-saturated and gas-saturated. Fig. 3 shows V_P vs. V_S for water-saturated and gas-saturated limestones with R^2 of 0.92 and 0.94, respectively, as eqs. (1) and (2).

$$V_S = 0.41V_P + 0.75 \quad , \tag{1}$$

$$V_S = 0.43V_P + 0.64 \quad . \tag{2}$$

Also, eqs. (3) and (4) were obtained for water- and gas-saturated dolomites with R2 of 0.91 and 0.93, respectively, as depicted in Fig. 4.

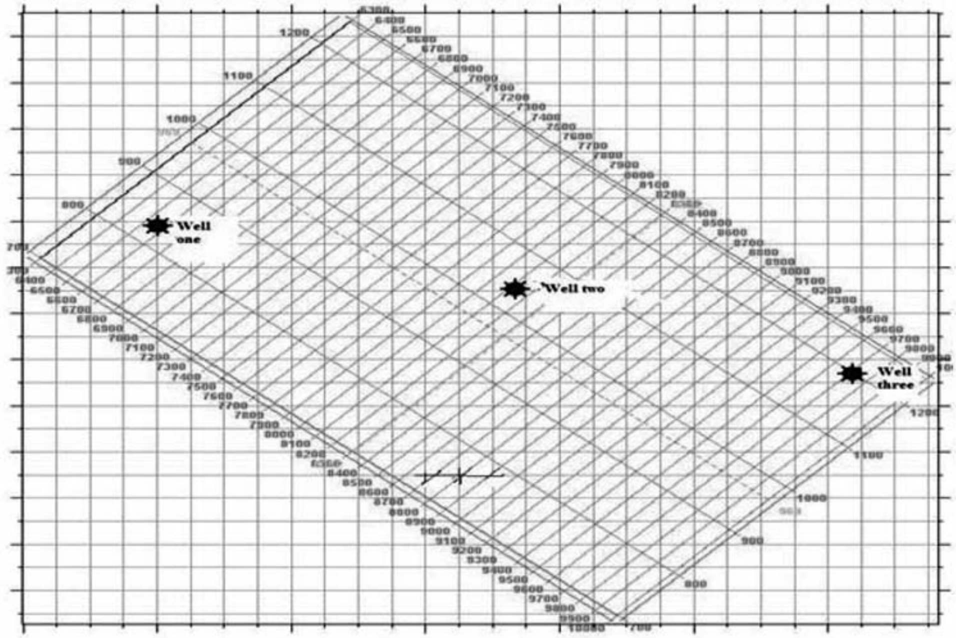


Fig. 2. The location of the three wells with respect to each other.

$$V_S = 0.44V_P + 0.72 \ , \tag{3}$$

$$V_S = 0.52V_P + 0.30 \ . \tag{4}$$

In Figs. 3 and 4, for water saturated regions the estimation of Castagna et al. (1993) for V_P and V_S has been presented as the broken line. As it can be seen, Castagna's relationship of V_P vs. V_S for water saturated limestones that is presented in eq. (5) estimates V_S values lower than the actual ones (Fig. 3, top). For water saturated dolomites, the Castagna et al. (1993) equation that is presented in eq. (6) estimates V_S lower than the actual values for $V_P < 5.5$ km/s, and higher than the actual values for $V_P > 5.5$ km/s (Fig. 4, top). Therefore, considering the different conditions of each region, it is better to calculate these relationships specifically for each region. Four general equations for water- and gas-saturated limestones and dolomites are presented in Table 1.

$$V_S = 0.0550V_P^2 + 1.0168\ V_P - 1.0305 \ , \tag{5}$$

$$V_S = 0.5832V_P - 0.0777 \ . \tag{6}$$

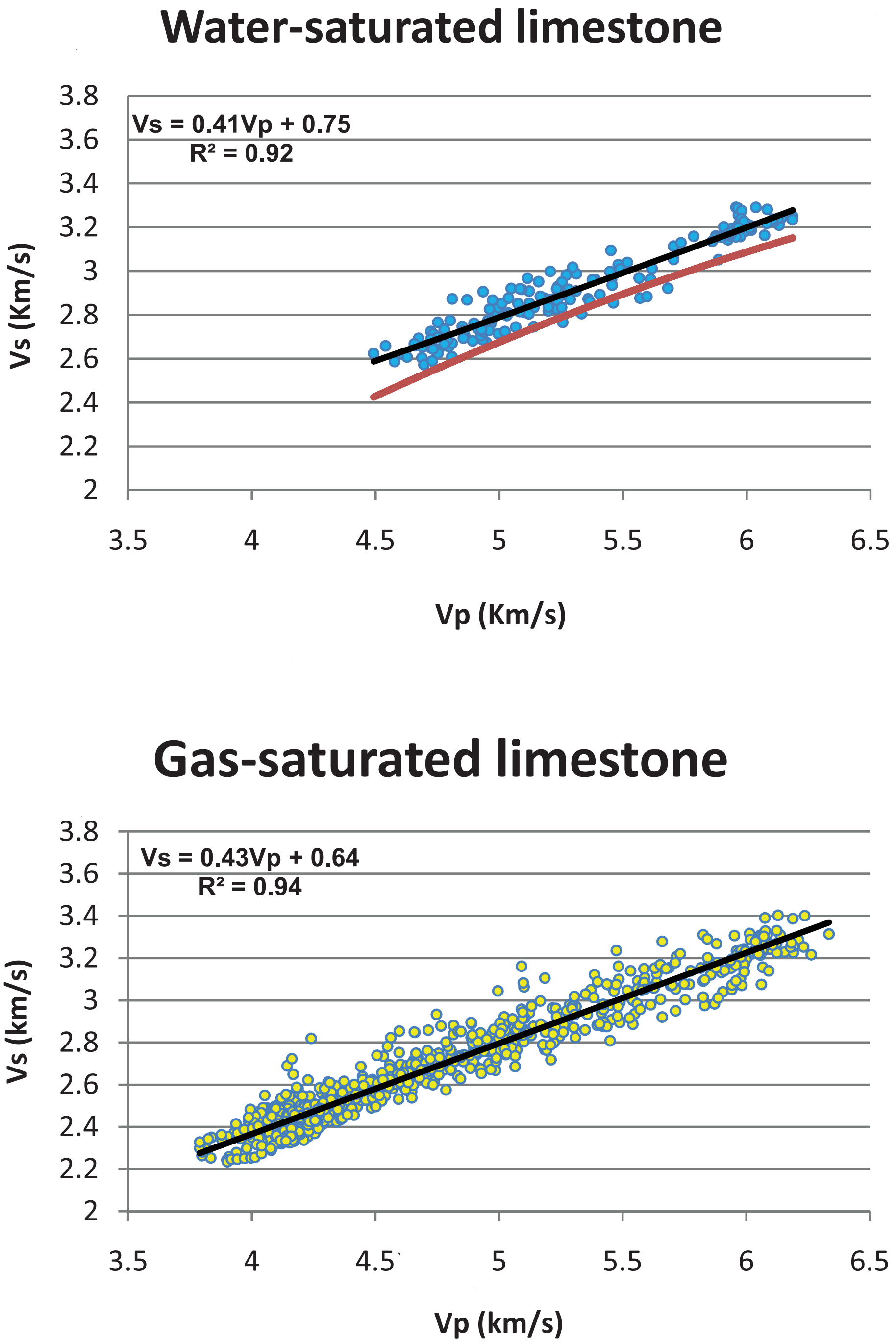


Fig. 3. Relationships between V_P and V_S in water- (upper) and gas- (lower) saturated limestones. In the crossplot related to water-saturated regions, the Castagna et al (1993) estimation of the relationship between V_P and V_S is presented as the broken line.

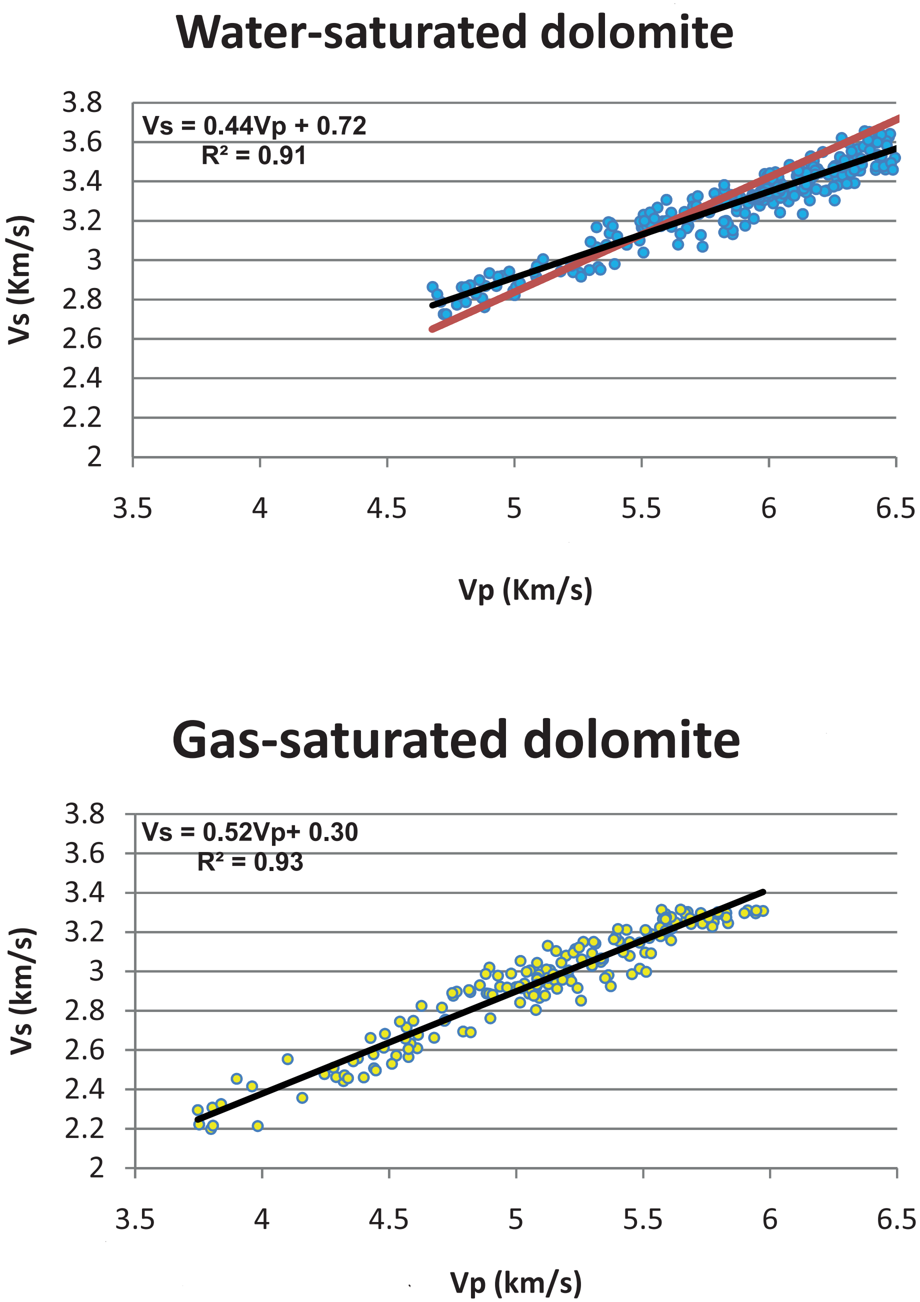


Fig. 4. The relationship between V_P and V_S in water- (upper) and gas- (lower) saturated dolomites. In the crossplot related to water-saturated regions, the Castagna et al. (1993) estimation of the relationship between V_P and V_S is presented as the broken line. The Castagna equation estimates V_S lower than actual values for $V_P < 5.5$ km/s, and higher than actual values for $V_P > 5.5$ km/s (upper).

Table 1. Relationships between V_P and V_S for water- and gas-saturated limestones and dolomites in the field of study.

	Water saturated	Gas saturated
Limestone	$V_S = 0.41V_P + 0.75$ $R^2 = 0.92$	$V_S = 0.43V_P + 0.64$ $R^2 = 0.94$
Dolomite	$V_S = 0.44V_P + 0.72$ $R^2 = 0.91$	$V_S = 0.52V_P + 0.30$ $R^2 = 0.93$

THE EFFECT OF GAS ON V_P AND V_S

Common wisdom holds that fluids have little or no effect on the properties of carbonate rocks, as these rocks have very high elastic moduli (Li et al., 2003). For isotropic rocks, Gassmann's theory (1951) predicts that the bulk modulus changes with saturation while the shear modulus remains unchanged. If the rock is anisotropic, the shear modulus will be changed 5 to 20% from dry to water or brine saturation in carbonates (Adam et al., 2006). Hence, in anisotropic rocks, both V_P and V_S are sensitive to fluid change. It is noted that the effect of elasticity on velocity is much greater than the effect of density. V_S increases with the increase of gas saturation due to the decrease of density and the absorption of deformation by free gas in pores (Hamada, 2004). The fact that V_P and V_S are changed with the increase of gas saturation make the ratio of V_P/V_S more sensitive to the change of fluid type than the use of V_P or V_S separately (Hamada, 2004). Thus, the presence of gas causes the velocity ratio to be smaller than the known ratio for each rock type (Kithas, 1976). In particular, for gas saturation the ratio of V_P/V_S is much lower (10-20%) than for liquid saturation (Gardner and Harris, 1968; Kuster and Toksöz, 1974a,b; and Tatham, 1982) and is consistent with the theory of Biot (1956a,b). The significant decrease in V_P/V_S values for gas- and water-saturated rocks suggests that the velocity ratio has the potential importance for detecting gas saturated intervals (Pardus et al., 1990; Eskandari et al., 2004). Analyses by Rafavich et al. (1984) of the dolomite data from the Williston Basin in eastern Montana, Western United States, indicate that not only gas does influence on properties of carbonate rocks but its effect is significant. Li et al. (2003) showed that carbonates have high velocities and relatively steady V_P/V_S ratios.

The effect of gas on V_P and V_S in the area of study

In this section, three crossplots are used to show the effect of gas on V_P and V_S and, subsequently, on their ratio. First, water- and gas-saturated samples are shown in the crossplot of ΔT_P vs. ΔT_S. Then, these samples are compared in two crossplots of V_P/V_S vs. V_P and V_S. It is noted that the equation of Wyllie et al. (1958) can take the following form:

$$\Delta T_P = \Delta T_f \phi + (1 - \phi)\Delta T_m \ , \tag{7}$$

where ΔT is the wave transit time and ϕ is the porosity. Knowing the transient time of compressional and shear waves in rock matrices and reservoir fluids (Table 2), and using the above equation, ΔT_P vs. ΔT_S can be crossplotted for different lithologies. Fig. 5 is ΔT_P vs. ΔT_S in μs/ft.

Table 2. V_P, V_S, V_P/V_S and Poisson's ratio for quartz, dolomite and calcite. Mineral velocities are calculated in zero porosity for an isotropic medium.

	V_P (km/s)	V_S (km/s)	V_P/V_S	Poisson's ratio	References
Quartz	6.06	4.15	1.6-1.7	0.17-0.26	1
Dolomite	7.05	4.16	1.8	0.27-0.29	2
Calcite	6.26	3.24	1.9	0.29-0.33	1

1) Anderson and Liebermann (1966), 2) Nur and Simmons (1969)

The three lines are limestone water baseline (blue), dolomite water baseline (red) and sandstone water baseline (green). Based on lithology and saturating fluid, the regions were classified into dolomite or limestone. Consequently, Fig. 5 shows the gas effect on dolomites and limestones in this region. Cyan, yellow and violet points show water- and gas-saturated limestone and water-saturated dolomite zones, respectively. In general, the points related to gas-saturated zones are below the baseline of the same water-saturated lithology. As seen in the upper segment of Fig. 6, samples related to gas-saturated regions have shifted to the left and lower than the regions related to the water saturated limestones and dolomites. As a result, gas-saturated samples are distinguished from water-saturated limestone samples by their lower V_P. In the crossplot of V_P/V_S vs. V_S related to the gas- and water-saturated samples, the results are completely reversed (Fig. 6, lower). As indicated previously, in response to an increase in gas saturation, V_S increases only slightly, unlike V_P. This causes the gas-saturated samples on the crossplot of V_P/V_S vs. V_S to be shifted to the right of and lower than the carbonates-related regions.

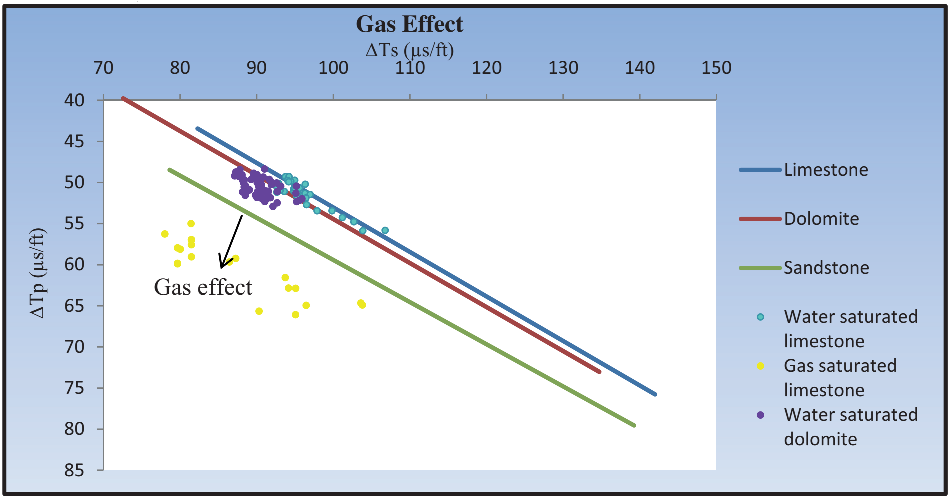


Fig. 5. Crossplot of compressional and shear wave transient times for different lithologies. The three lines are limestone water baseline (blue), dolomite water baseline (red) and sandstone water baseline (green). Cyan, yellow and violet points show water- and gas-saturated limestone and water-saturated dolomite zones, respectively. In general, points related to gas-saturated zones are below the baseline of the same water-saturated lithology.

THE EFFECT OF DOLOMITIZATION ON V_P AND V_S

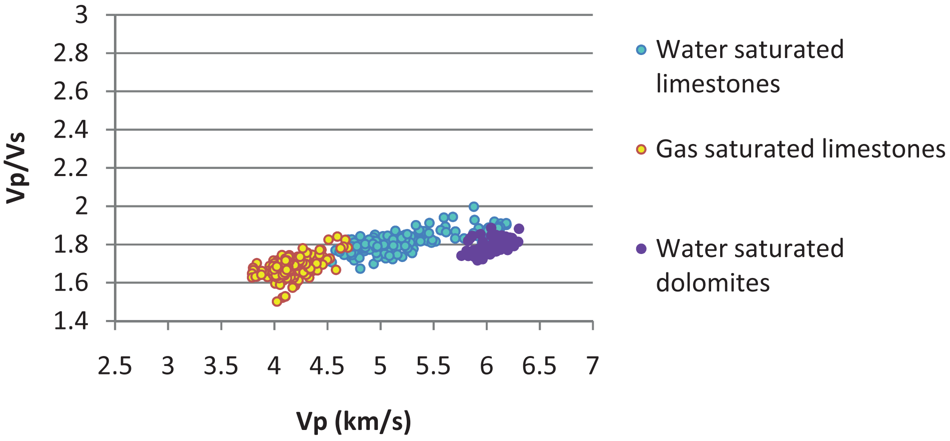
Significant volumes of world hydrocarbon reserves occur in dolomites, so distinguishing them is very important in petroleum exploration. Since the velocity of seismic waves depends on porosity, percentage of saturation, fluid type in pores, pressure differences, and pore geometry in addition to lithology, it is not possible to specify lithology precisely in crossplots of V_P vs. V_S. On other hand, both laboratory and well logging experiments demonstrate it is possible to separate limestones from dolomites on the basis of the velocity ratio, V_P/V_S, or, consequently, Poisson's ratio. One of the results of dolomitization is an increase in porosity (about 13%) (Kithas, 1976). Kithas (1976) used different examples from Winkler and Ector counties in Texas to determine Young's modulus, velocity, and Poisson's ratio in dolomites. In carbonates, Rafavich et al. (1984) showed that V_P/V_S can be used to discriminate limestones from dolomites. Pardus (1990) showed that the dolomitization of limestones decreases the V_P/V_S ratio from 1.9 to 1.8.

The effect of dolomitization on V_P and V_S in the area of study

In Iran, most reservoirs are carbonate rocks including limestones and dolomites. According to Table 2, V_P in dolomites is higher than in limestones; but V_P/V_S in dolomites is lower than in limestones. Therefore, dolomitization of calcite causes its location in V_P/V_S vs. V_P (or V_S) crossplot to be shifted to the right side of carbonates-related regions (Fig. 6, upper) and they can be distinguished from limestones. As seen in this figure, V_P in water-saturated limestones varies from 4.5 to 6 km/s; however, it varies from 5.5 to 6.5 km/s for water-saturated dolomites. In the crossplot of V_P/V_S vs. V_S (Fig. 6, lower), V_S varies from 2.5 to 3.5 for water-saturated limestones, but it varies from 3 to 3.5 for water-saturated dolomites. Fig. 7 shows the general effect of gas and dolomitization on the velocity of seismic waves for carbonates in the field of study.

CONCLUSIONS

Three wells in one of the gas reservoirs in the Persian Gulf, Iran, were used to study V_P and V_S of limestones and dolomites with different fluid saturations. From these studies, following conclusions can be made: (1) Eqs. (1) and (2) can be used to predict the relationships between V_P and V_S for water- and gas-saturated limestones, and eqs. (3) and (4) for water- and gas-saturated dolomites, respectively. (2) These same equations can predict V_S for limestone and dolomite rocks with R^2 of more than 0.90. (3) Relationships between V_P and V_S are linear for both limestones and dolomites (both gas- and water-saturated cases) in the area understudy. (4) As shown, Castagna's relationships (Castagna, et al., 1993) estimated V_S less than actual values for limestones and dolomites in the area under study. (5) There are many problems in lithology and fluid determination based on seismic data. Because of interference effect, every bed thickness must be enough to be seen on seismic data. Moreover, only if the special lithology has acoustic impedance different from acoustic impedance of surrounding lithology, the seismic methods can distinguish it. In the determination of fluid change, the new fluid saturation must be enough to be recorded on seismic data as flat spots. Crossplots of V_P/V_S vs. V_P and V_P/V_S vs. V_S show the effect of gas in carbonates. It was also shown that the trend of gas saturation samples in the crossplot of V_P/V_S vs. V_P is different from that of V_P/V_S vs. V_S. Crossplots of V_P/V_S vs. V_P and V_P/V_S vs. V_S can be used to separate water saturated dolomite zones from water saturated limestone zones. It is more difficult to separate gas saturated dolomite zones from gas saturated limestone zones in crossplot of V_P/V_S vs. V_S, because in response to an increase in gas saturation, V_S increases only slightly. So two zones are very close to each other.



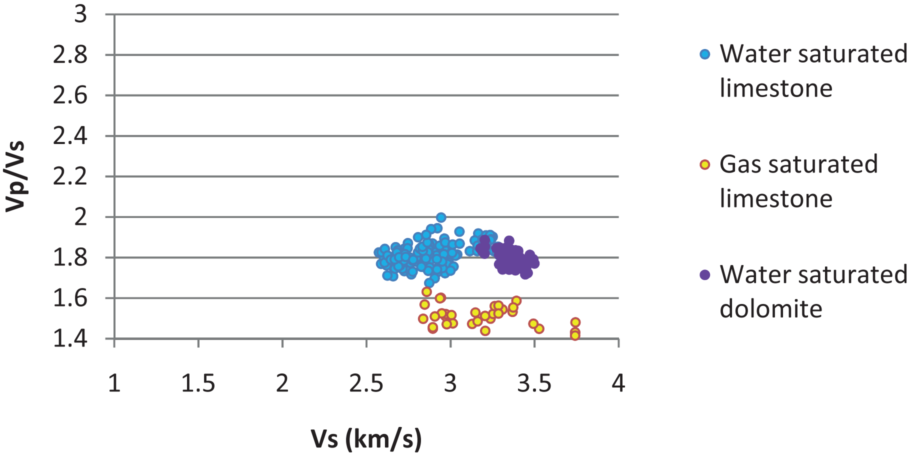


Fig. 6. Crossplot of V_P/V_S vs. V_P (upper) and V_S (lower). In the crossplot of V_P/V_S vs. V_P, samples related to gas-saturated regions have shifted to the left and lower than the regions relating to the carbonates due to lower V_P and are distinguished from water-saturated limestone samples. In the crossplot of V_P/V_S vs. V_S, the gas saturated samples shift to the right (higher V_P) and lower than the carbonates regions (lower figure).

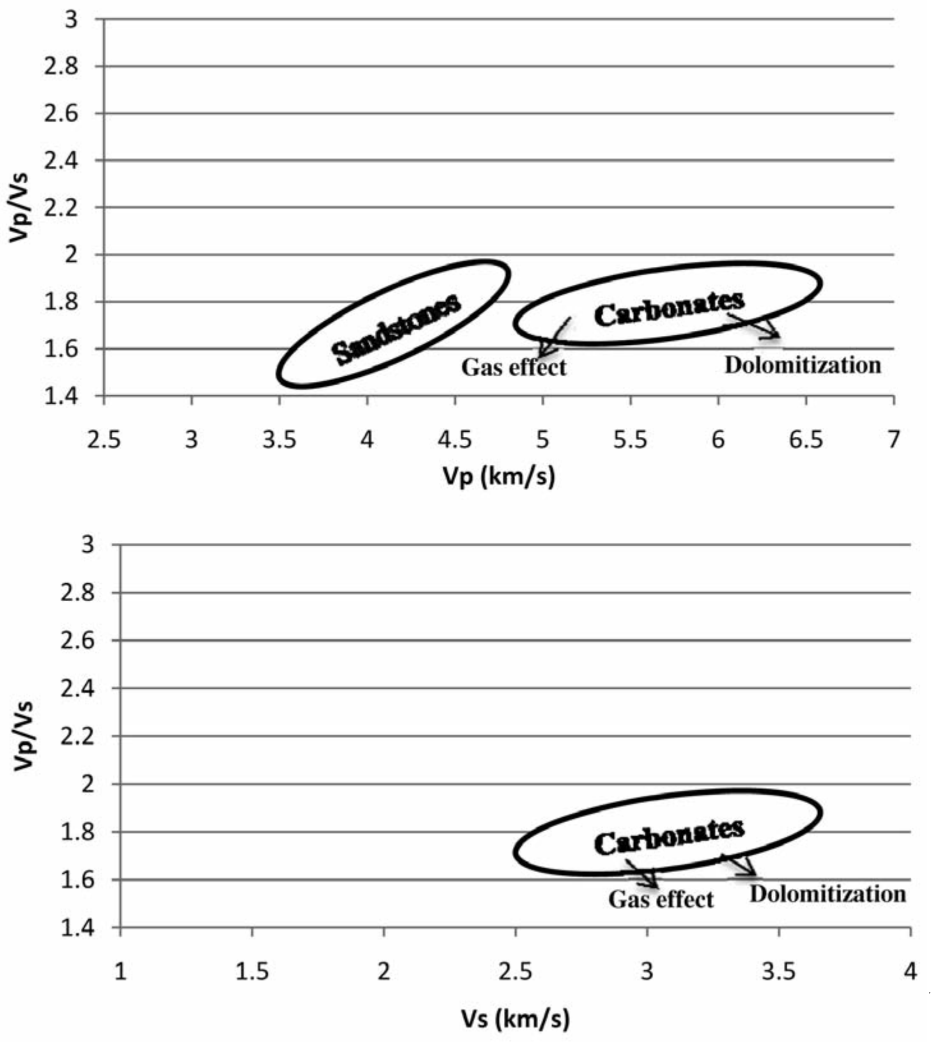


Fig. 7. General results of the gas and dolomitization effects on the velocity of seismic waves for carbonates. The location of sandstones in the crossplot of V_P/V_S vs. V_P was determined according to the results of Li et al. (2003).

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