Gaseous reservoir horizons determination via Vp/Vs and Q-Factor data, Kangan-Dalan Formations, in one of SW Iranian hydrocarbon fields

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Abstract

An important method in oil and gas exploration is vertical seismic profile (VSP) to estimate rock properties in drilling well. Quality factor is also the crucial point of seismic attenuate in VSP data. In the present study, this factor was used to evaluate the hydrocarbon potential of Kangan Formation in one of the Persian Gulf oil fields using VSP zero offset method. Quality factor was estimated using VSP spectral ratio method. Density and porosity logs are also used to determine lithology and reservoir fluid types. Analysing Vp/Vs ratio changes is a useful tool to detect hydrocarbon accumulation. These points marked by high amplitude energy in seismograms in correlation with petrophysical logs. According to Vp/Vs plots and geological logs of the field revealed that Vp/Vs ratio is increased at depths indicating hydrocarbon presence. Data are showing good correlation to petrophysical logs. Therefore, VSP method can be applied as a suitable alternative method to find hydrocarbon reserves in those boreholes without petrophysical logs.

Keywords: *Vertical Seismic Profile (VSP); Kangan Formation; Reservoir Quality Factor; Hydrocarbon Reservoir*

Introduction

The vertical seismic profile (VSP) method starts since 1960s. This method is detected the upscalind and down scaling reflected waves according to their distribution (Society of Professional Well Log Analysts, 1975; Hinds *et al*., 2002; Sheriff and Geldart, 2002). At the present time there are useful papers and publications about the basic information of VSP method (Kennett *et al*., 1980; Oristaglio, 1985; Daley *et al*., 1988; Hinds *et al*., 2002). The method may be used as the complementary or comparable method for surface seismic data due to its high resolution potential (Brewer, 2000, 2002) since the reflected waves can be detected by the zero offset receiver at the surface (Sengel, 1981; Hardage, 2000; Kearey *et al*., 2002; Milsom, 2003). This capability is between the resolution factor of well logging and surface seismic methods. In this method there is not presented the doubts of the place of receiver and source at the surface and the target zone as the main factor effects on the resolution ability. This method can be applied as the estimation of rock properties near the well bore (Hardage, 1983), and also the comparison purposes to well logs (Hackert & Parra, 2002). Fracturing studies (Becker and Perelberg, 1986; Corrigan *et al*., 1987; Majer *et al*., 1988), refracted rays correlation (Nichols *et al*., 2010), determination of sonic velocity in layers comparing to sonic logs (Bulant, & Klimeš, 2008), seismic resistant of the structure to evaluate hydrocarbon potential in depth (Blackburn *et al*., 2007; Trice, 2014), attenuation and quality factor estimation (Winkler and Nur, 1982; Pride and Berryman, 2003; Pride *et al*., 2004; Zhang & Stwart, 2007) are the main applications of VSP method.

Seismic attenuation in hydrocarbon fields related to movability of fluids, viscosity and volumetric modulus in the pores (Kumar *et al*., 2003). Now it can be solely attracted all attentions and so applied by numerous geologists and petrophysists in their researches in the worldwide. So, here it is preferred to note some of these research papers: in Costa Rica to study of the trench base, subduction and sedimentary wedge (Shipley and Moore, 1986); Salton Sea of California (Daley *et al*., 1988); Trough wedge of Nankai (Moore *et al*., 1990); Fluids role in the tectonic of transgressive wedge (Westbrook, 1991); buoyancy distribution, fluid migration and fault resistance in the North of Barbados ridge (Shipley *et al*., 1994) and depth and seismic characteristics (Moore *et al*., 1997); Geothermal reservoir (Feighner *et al*., 1999); subsurface gas reservoir (Daley *et al*., 2000); coal bed in NW of Red Deer, Alberta (Richardson & Lawton, 2003); comparison of surface and VSO data in Qheshm region (Mokhtari, & Pourhossein, 2003); VSP inversion (Schuster *et al*., 2004); Gas hydrates in Mackenzie Delta, NW of Territories , Canada (Sakai, 1999; Milkereit *et al*., 2005); 3D wave equations in poly-modal offsets (He *et al*., 2006); shallow depth VSP in West Castle River, Sought of Alberta (Miong *et al*., 2007); reconstruction of salt dome in Sigsbee Salt area, Mexico Gulf (Vasconcelos *et al*., 2008); anisotropic and attenuation of seismic waves in heavy oil and potash ore (Saskatchewan) in western Alberta (Zhang, 2010); CO2 storage in Ketzin region, Germany (Yang, 2010); Turbidite reservoir characteristics in Brazil platform (Marques *et al*., 2011); VSP analysis in western Cameron region of Louisiana platform (Kreona, 2012); reservoir evaluation of Murzuk Basin in Libya (Mohamed *et al*., 2013); inversion modeling of Permian Basin, Texas (Smithyman *et al*., 2015); and comparison of walkaway of poly-components of VSP data to zero-offset and AVO amplitude (versus offset) (Wu *et al*., 2015).

The nature of seismic waves is elastic or acoustic waves which are mechanical disturbances (elastic vibrations) and so can be used to diagnose the type of materials (Nazarchuk *et al*., 2017). Elastic vibrations in liquids and gases are characterized by one of the following parameters: change in pressure, or density; particle shift from an equilibrium state; vibration motion velocity; or shear potential. A typical feature of vibrations in a solid is the change in stresses, displacement of its particles and shear potential. In a seismic project, elastic waves are sent into the interior of the earth and their reflections are recorded and processed to interpret the subsurface structure. For this purpose, different arrays of the sources and receivers are proposed (Fig.1): 1)- Zero offset that the source is above the receiver; 2)-a distance between the source and receiver; 3)-the source may be moveable, walk away, but the receiver is fixed; 4)-move above the borehole to detect the geometry of deviated and the source is above the receiver which are located at different lateral position; 5)-the source above the salt dome and far from the rig to determine the sediments near the structure; 6)-the source is the bit vibration while drilling; 7)-poly-components profile which is the source far from receiver group (Dobrin & Savit, 1988; Zimmerman, and Chen, 1993; Christie *et al*., 1995; Haldorsen *et al*., 1995; Schlumberger, 2014). However it should be noted that in some cases the behavior of the environment can be considered as an important and useful factor to get more information. One of these is polarization of the shear wave by subsurface features (Christie *et al*., 1995) such as fractured surfaces that may contain information about the anisotropy and the crack orientations (Crampin, 1984).

The present work is an attempt to apply VSP method to determine reservoir horizons of the Kangan Formation in one of Iranian hydrocarbon fields, in the Persian Gulf.

Area understudy

The area understudy is one of Iranian oil fields located at the Persian Gulf. The Lower Kangan (Early Triassic) and Upper Dalan (Late Permian) formations as the main reservoirs of the field are divided into 4 zones: K1, K2, K3, and K4.

Methodology

The borehole understudy is located in 14th phase of Southern Pars gas field, Persian Gulf. The field seismic data were gathered using gun air as the explosive source (90m far from the hole) with minimum phase of the wavelet. The tool is ASL (Avalon Sciences Ltd.), manufactured in UK with 4 shuttles containing 3-vectors geophone type in each one. The distance of geophones is 15m and the array is zero offset. Other properties are given in Table 1.

As it is indicated in table 1, data gathering was started from -400m (free sea level) and continued to -3200m.

In the present paper, petrophysical interpretation was made based on seismic data processing (Fig. 2), quality factor, depth correlation of well logs, initial calculation, parameters selection and environmental corrections.

Data quality control and loading shots data were made separately for each depth using seismic trace processing and selecting the best data without any noise and suitable energy in raw data.

The quality of data was improved in post stacking stage and compared with pre stacking data (Fig. 3).

Geometry and frequency analyses indicated that the best range of high quality frequencies of the source is 15-30 Hz. All other processes such as shot checks, first arrival wave picking (based on time and space differences), velocity analysis, AGC phenomenon (automatic gain control), upscaling and down scaling separation (F-K filter), hodograms (rotation analysis of geophone vectors), Deconvolution (the process of extracting the reflectivity function from the seismic trace to improve the vertical resolution and recognition of events) were carried out to interpret the seismic results.

After check shot correction in this well (Fig. 4A) a zero phase wavelet with 120 ms length and 10 ms taper length extracted using seismic data (Fig. 4B). Extraction window is 1300 ms to 1852 ms; also the extraction traces include inline: 1271-1291 and crossed line: 8105-8125.

Table 1. Field seismic data properties

Survey type	Zero offset VSP
Down hole recording length	5000ms
Down hole sampling rate	1ms
Top of survey	400m
Bottom of survey	3235m
Number of shots	68
Number of down hole traces	272
Kelly bushing	27.7m
Ground level elevation	0m
Type source	Air gun

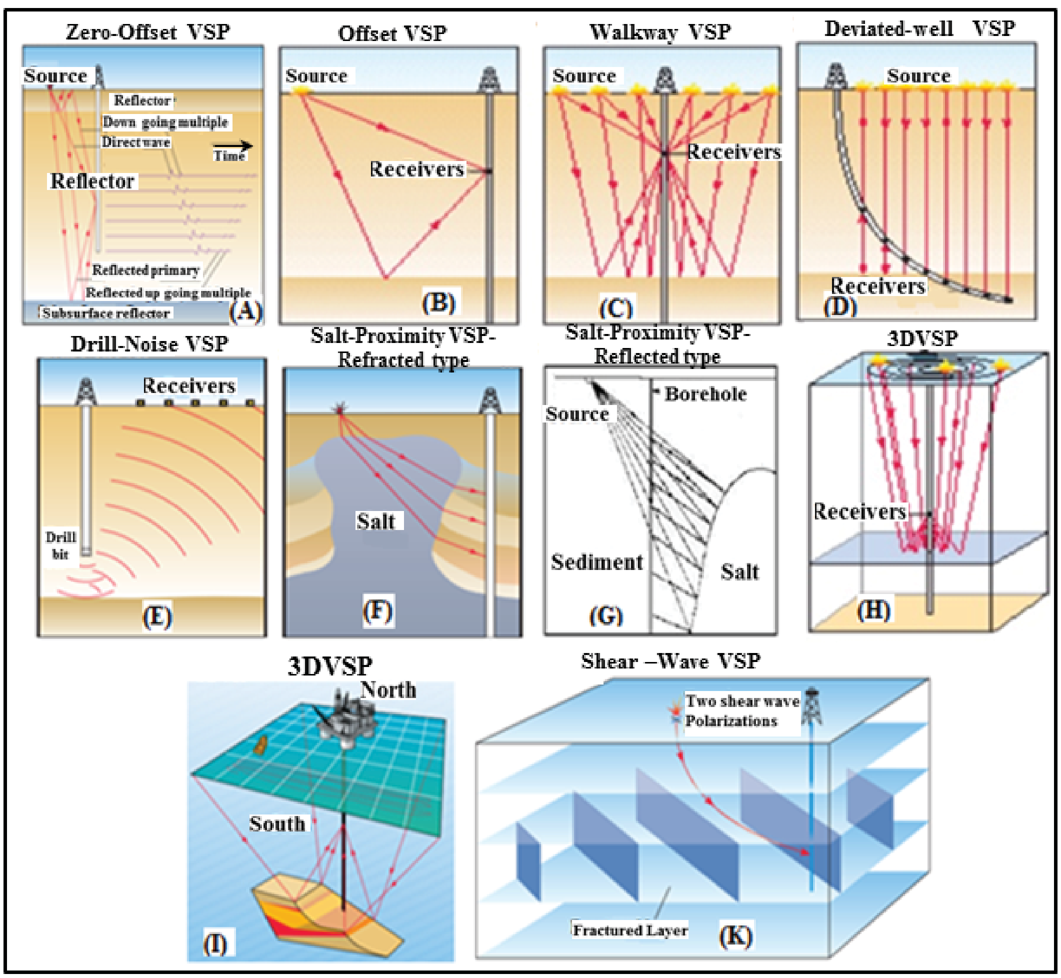

Figure 1. VSP methods based on the source and receivers positions. The figures A- F, I and K from Christie *et al*., 1995, G from Dobrin & Savit, 1988, and H from Schlumberger, 2014, were adopted.

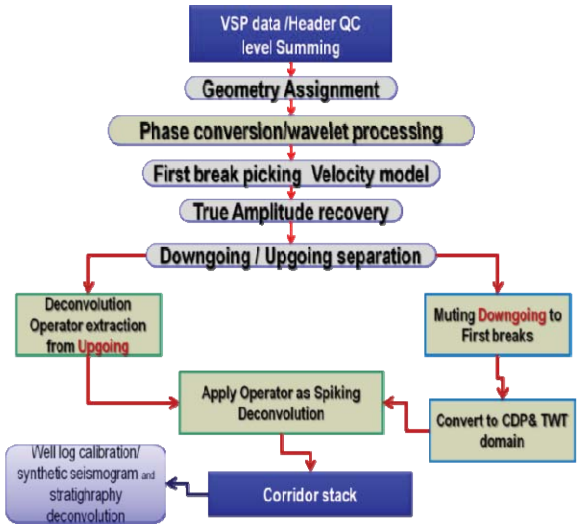

Figure 2. Flowchart of seismic data processing

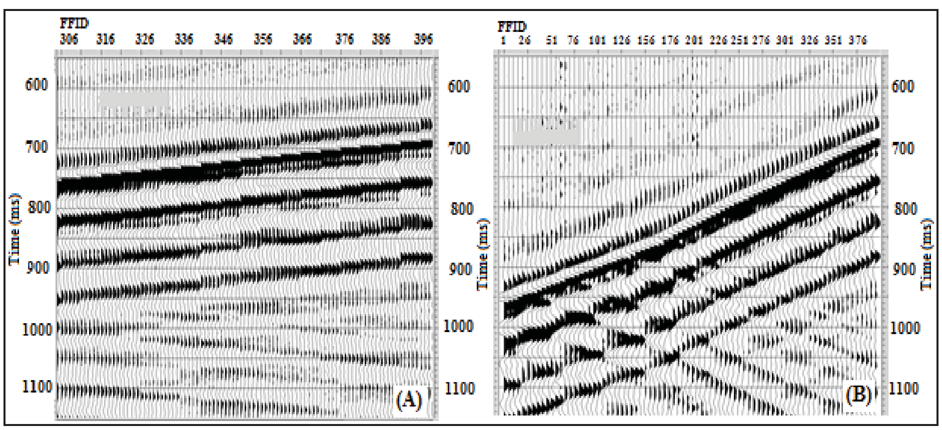

Figure 3. The comparison of (A) pre and (B) post stacking data

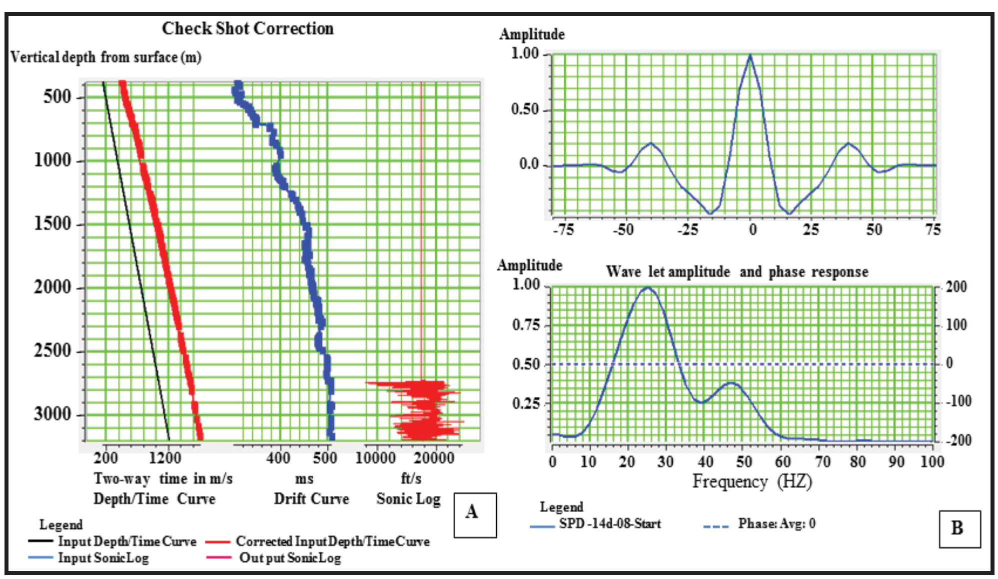

Figure 4. Check shot correction (A) and extracted constant phase wavelet from seismic data (B) alone around well no. SPD-10-08.

Figure 5A shows the correlation after check shot correction in this well. As it is clear, 21 ms downward shift is necessary. Figure 5B shows synthetic seismogram after mentioned shifting.

Finally, minor stretch and squeeze is applied to get more consistency between seismic data and synthetic seismogram (Figure 6).

Wave attenuation and Q-factor

It is possible to estimate wave attenuation by environmental absorption or quality factor from VSP data. Wave attenuation is very important in seismic data processing since it can be a direct indicator of hydrocarbon presence. This attenuate is related to the movability potential of fluid, viscosity and volume fluid modulus (Kumar *et al*., 2003; Pride & Berryman, 2003). Therefor they impact on the permeability estimation (e.g., Winkler & Nur, 1982; Pride *et al*., 2004).

Ten methods for the computation of attenuation have been investigated, namely: amplitude decay, analytical signal, wavelet modeling, phase modeling, frequency modeling, rise-time, pulse amplitude, matching technique, spectral modeling and spectral ratio. The reliability of each of these methods in estimating correct values of *Q* using three synthetic VSP seismograms for P-waves plane with different noise contents was studied (Tonn, 1991).

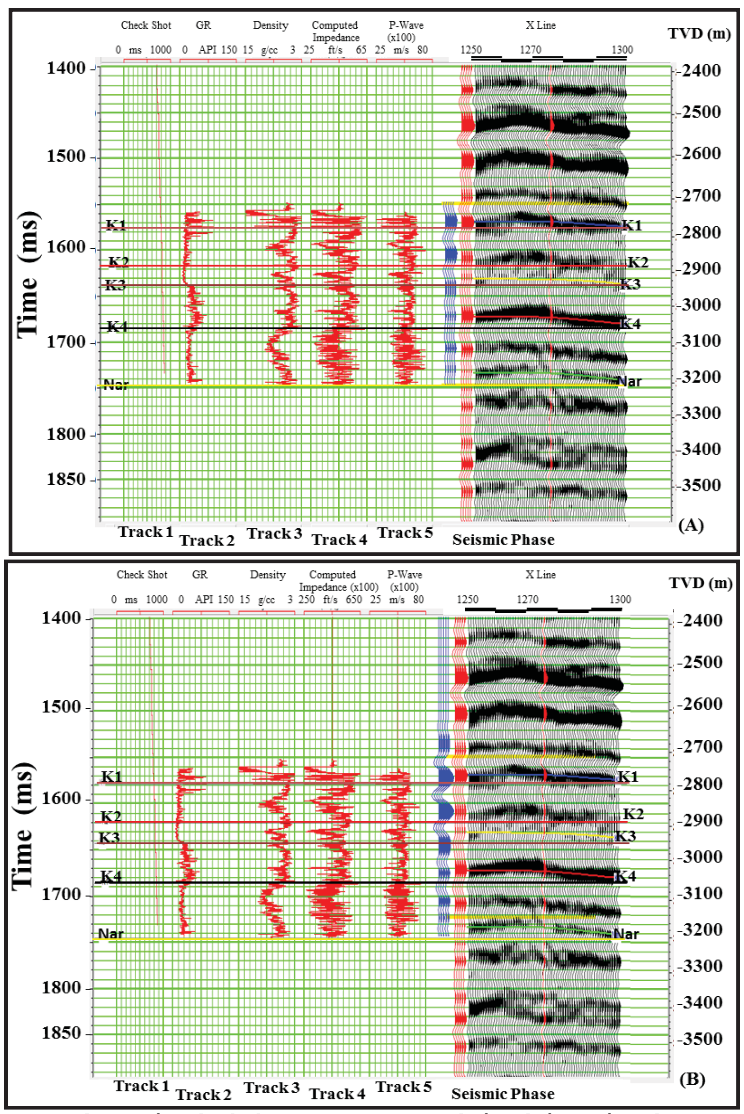

Figure 5. Synthetic-seismic correlation after check shot correction (A), and after shifting of synthetics (B) in well no. SPD-10-08.

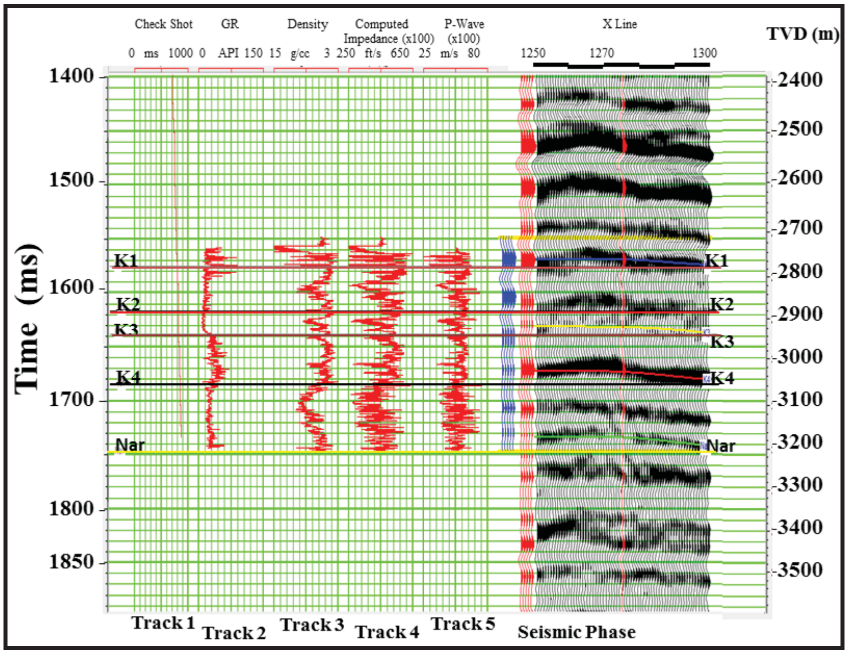

Figure 6. Final synthetic-seismic correlation in well no. SPD-10-08.

In the present work the quality factor (Q) was estimated by VSP zero- offset since the surface seismic data will be caused a high certainty and limitation. Therefore VSP data is preferred due to less travelling time. The low quality factor is correlated to the hydrocarbon presence. Q-value is lower in saturated rocks than unsaturated. By comparing of Q_p and Q_s is able to determine saturation variation and fluid type (Zhang, & Stwart, 2007). However, lithostatic pressure and temperature increasing can be directly affected on Q_p data.

Q-factor-

Seismic quality (Q) or attenuation factors are useful to apply for amplitude analysis and improve resolution and also to get information about petrophysical characteristics of the reservoir such as lithology, saturation, permeability and pore pressure (Calderón-Macias *et al.*, 2004). There are available several ways to estimate quality factor such as:

1-Spectral ratio method (Tonn, 1991; De *et al*., 1994) - Tonn (1991) using different numerical methods (among them spectral modeling and spectral ratio (Bath, 1974)) estimated the quality factor Q from *VSP* except in the presence of thin layers (This method was applied in the present research work).

2-Plane harmonic inhomogeneous waves (White, 1980) - In this technique the harmonic results of signals in two depths (1 and 2) will be the function of transition H_{12} and its inverse H_{21}. So it can be written as:

$$H_{12}(f) = \frac{\text{Cross power spectrum (1,2)}}{\text{Power spectrum (1,1)}} \tag{1}$$

The cross power spectrum (1, 2) is the inverse of cross power spectrum (2, 1) and therefore:

$$\ln\left[\frac{H_{21}(\omega)}{H_{12}(\omega)}\right] = (\text{const.}) - m\omega \tag{2}$$

$$m = \frac{X_2 - X_1}{cQ} = \Delta t / Q \tag{3}$$

3- Frequency shift method (Quan and Harris, 1997; Li *et al*., 2015; Oliveira *et al*., 2015) - The central-frequency shift method estimates *Q* by observing the shifting quantity of the central (Quan & Harris, 1997) or peak frequency (Zhang & Ulrych, 2002) from a reference. The equation of central frequency shift (CFS) and peak frequency shift (PFS) methods was modified (Li *et al*., 2015) to provide the basis of reasonable accuracy and robustness of seismic data. Li *et al*. (2015) have derived an approximate equation combining Q and variance of dominant and central frequencies, and suggested a new method that called the dominant and central frequency shift (DCFS) method. They demonstrated that the method is useful guide in hydrocarbon detection and reservoir characterization.

4- The spectral ratio technique (Bettinelli & Puech, 2015) - This approach is usually used to estimate the Q factor and appears to be a fast and robust approach (using the new optical fiber seismic acquisition system where the density of traces is very high). However does not allow a stable *Q*-value characterization when the receiver interval is short as well the spectral division is often very dependent on the selected frequency range and the choice of the frequency bandwidth.

5-Analytical signal (Haase, & Stewart, 2004, 2005; Samieh, & Ghasem Al askari, 2010; Bigdeli Tabar, 2012) - In this case the role of stratigraphic attenuation (scattering) in Q-estimation is investigated. Based on scattering type the best condition can be selected. Errors in Q-estimation by the analytical signal method appear to be caused by insufficient moveout compensation. Tonn (1991) pointed out that, when true amplitude recordings are available, the analytical signal method is superior.

6- Drift time equation (Stewart *et al*., 1984; Keehn, & Kanasewich, 1987) - The discrepancy between the sonic arrival time and the seismic arrival time grows with depth (called as drift). There have been various explanations for drift (Stewart *et al*., 1984) which may be caused by variations in layer thicknesses, intrabed multiples, time picking of first arrivals, and attenuation.

7-Sparse equation method (Koskulics *et al*., 2012; Zhao *et al*., 2016) - Seismic imaging has many applications in civil engineering, risk hazard, waste storage monitoring, oil exploration and tectonophysics. Among the different seismic imaging methods the full waveform inversion aims to exploit the full information content of seismic data through the complete resolution of the partial differential wave equation. Frequency-domain solutions of the wave-equation for frequency-domain of full-waveform inversion (FWI) are: Frequency-domain iterative solvers (Plessix, 2009); frequency-domain direct solver (Ben-Hadj-Ali *et al*., 2008); hybrid direct/iterative methods based on the combination of direct and iterative solvers (Haidar, 2008; Sourbier *et al*., 2011); time-domain approach and Fourier Transform (Nihei and Li, 2007; Sirgue *et al*., 2008).

8- Experimental Equation method (Waters, 1981) - It is based on the experimental relation between Qp and Vp (ft/s):

$$\frac{I}{Q_P} = \left[\frac{1000}{V_P}\right]^2 \qquad (4)$$

There is also a relation between Qp and Qs (Udias, 1999):

$$\frac{Qs}{Qp} = \frac{4}{3}\left[\frac{Vs}{V_P}\right]^2 \qquad (5)$$

The investigations proved that no single method is generally superior. Rather, some methods are more suitable than others in specific situations depending on recording, noise or geology. The analytical signal method has been demonstrated to be superior if true amplitude recordings are available. Otherwise spectral modeling or, in the ‘noise-free’ case the spectral ratio method, is optimal.

Finally, two field VSPs in sediments are investigated. Only in the case of the highest quality VSP can significant information be deduced from the computed attenuation.

Comparing Vp/Vs and Poisson ratio with Q factor

The sensitivity of Vp/Vs to flow nature is higher than each parameter (Hamada, 2004). To determine Vs from Vp there are several relations which are varied to the reservoir condition. Based on these conditions in the area understudy three cases are considered. For mudstone, limestone and dolomite, the equation of Castagna *et al*. (1993) was used:

Mudstone:

$$V_S = 0.8621 \times V_P - 1.172 \qquad (6)$$

Carbonate:

$$V_S = -0.055 \times V_P^2 + 1.017 \times V_P - 1.031 \qquad (7)$$

Dolomite:

$$V_S = 0.583 \times V_P - 0.07776 \qquad (8)$$

The Poisson ratio is also important in elastic environment definition. This ratio can be considered as an indicator for hydrocarbon and is calculated directly from Vp and Vs:

$$\sigma = \frac{1}{2}\frac{(VP/VS)^2 - 2}{(VP/VS)^2 - 1} \qquad (9)$$

It should be noticed that Vp/Vs ratio in heterogeneous condition can be less than $\sqrt{2}$ and in the case of gas saturated will be decreased to 1.3 (Uyanik, 2010).

Mapping of Interpretation Results

Time Mapping

The interpreted horizons in the phase 14 boundary were gridded using convergent interpolation method and grid cells are assigning as 3D cube geometry which is 6.25 × 25m. The resulted time surface generated of K1, K3, K4 and Nar Member are shown (Fig. 7). As it is seen in these maps, the horizons are dipping from southeast towards northeast that shows the study area is located in the northeastern flank of the South Pars structure.

Time Thickness Mapping

Time thickness maps of the main horizons were generated to have an idea about overall thickness trends and to revise interpretation results (Fig. 8). As indicated, time thickness of K1 and K2 intervals is generally increasing from southeast towards northeast of the study area. K3 zone shows its minimum thickness mainly in the central parts and in the eastern edge of the study area. In contrary, K4 zone becomes thicker in the center of the study area.

Synthetic Seismogram Generation and Well to Seismic Tie

This part shows the calibration of well to seismic data using extracted wavelet and corrected check shots. Figure 9 shows the drift between raw check shots and derived TDR from sonic log before and after correction.

Figure 10 shows the extracted wavelet for inversion. This is the average wavelet which is extracted from all wells. Figure 11 shows the calibrated synthetic seismogram along with extracted seismic trace along well SPD-10-08.

The attenuate rock capability on seismic wave is estimated by quality factor (Q). In spite of high uncertainty of quality estimation by surface seismic data, VSP with low offset data is one of suitable method for this. The quality factor for P-wave (Qp) depends on fluid characteristics (saturation and fluid type) in the pores in comparing to S-wave.

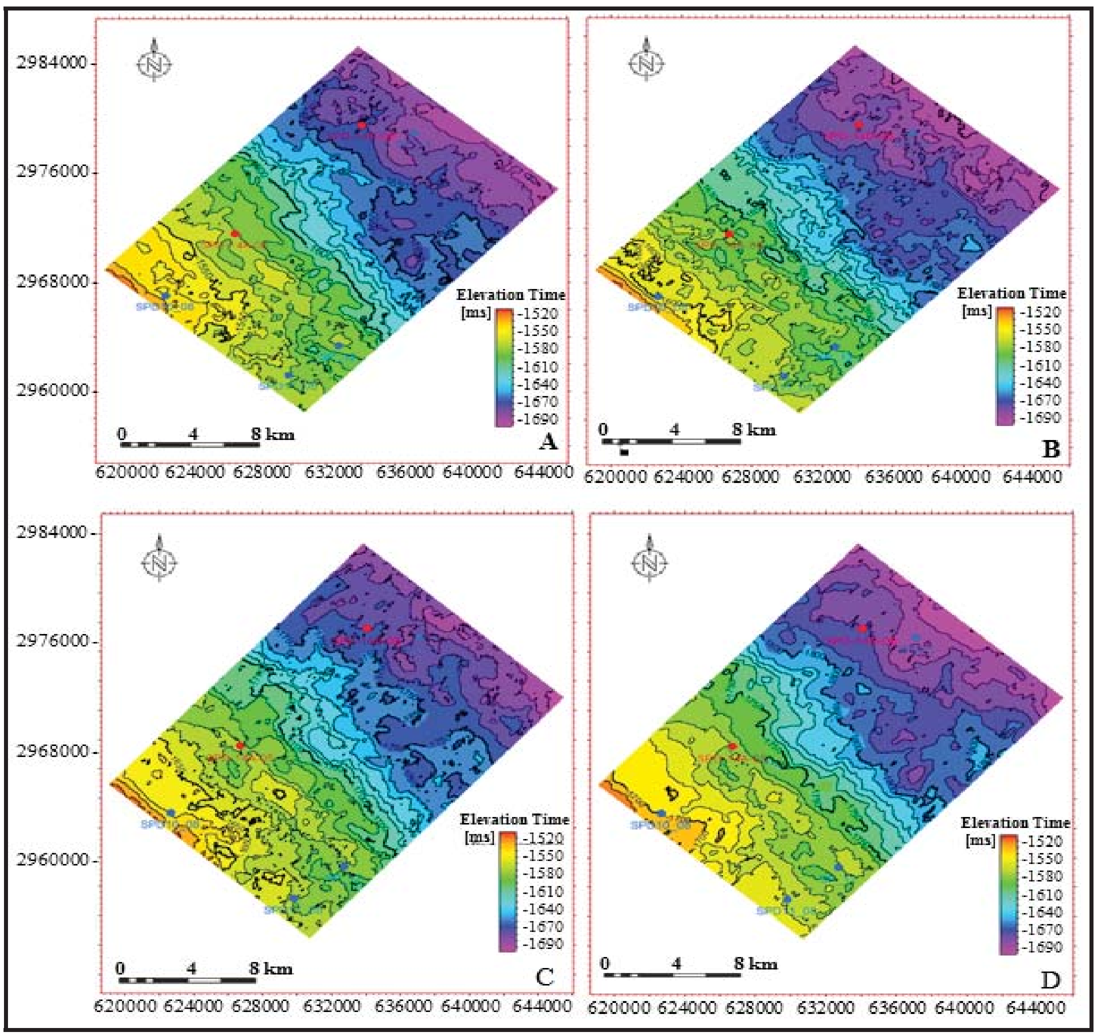

Figure 7. TWT maps of (A) K1 horizon; (B) K3 horizon; (C) K4 horizon; and (D) Nar member.

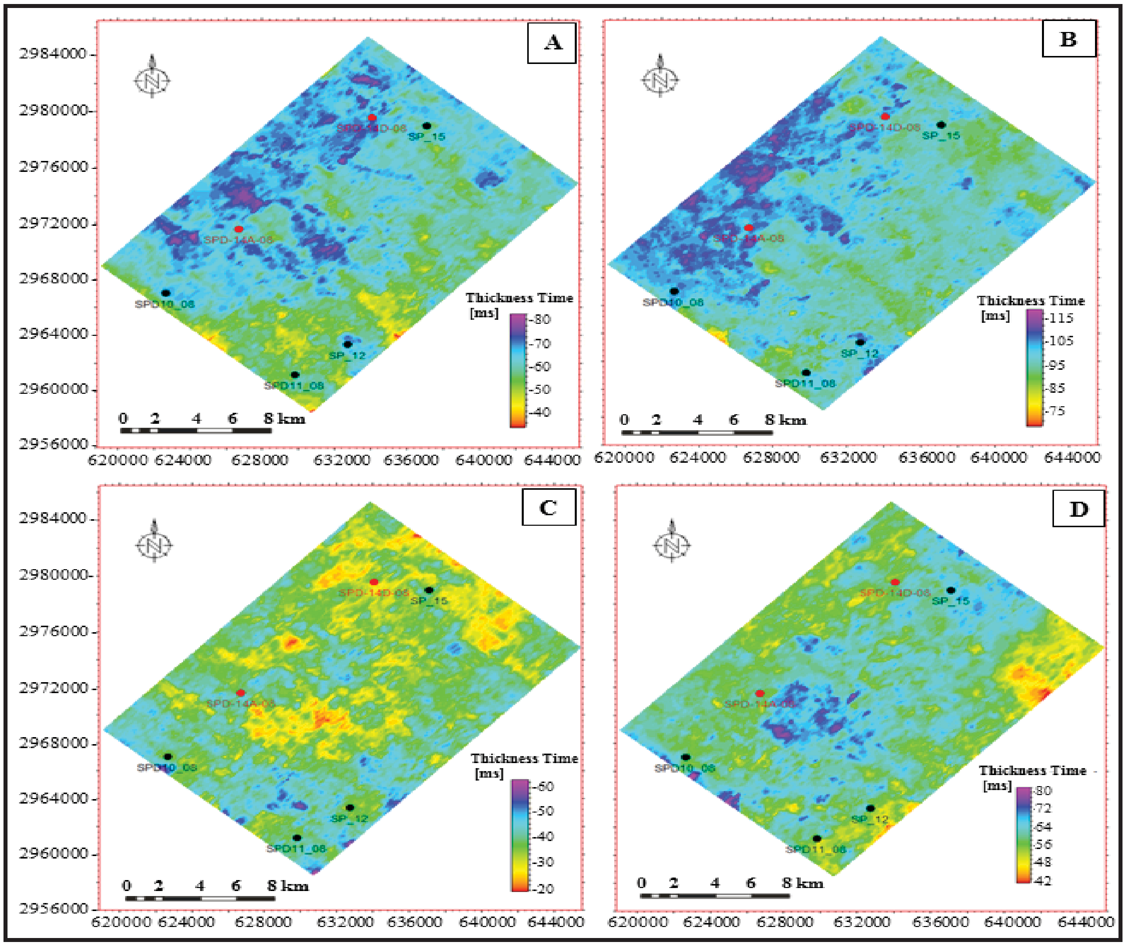

Figure 8. Time Thickness maps of (A) K1-K3; (B) K1-K4; (C) K3-K4; and (D) K4-Nar.

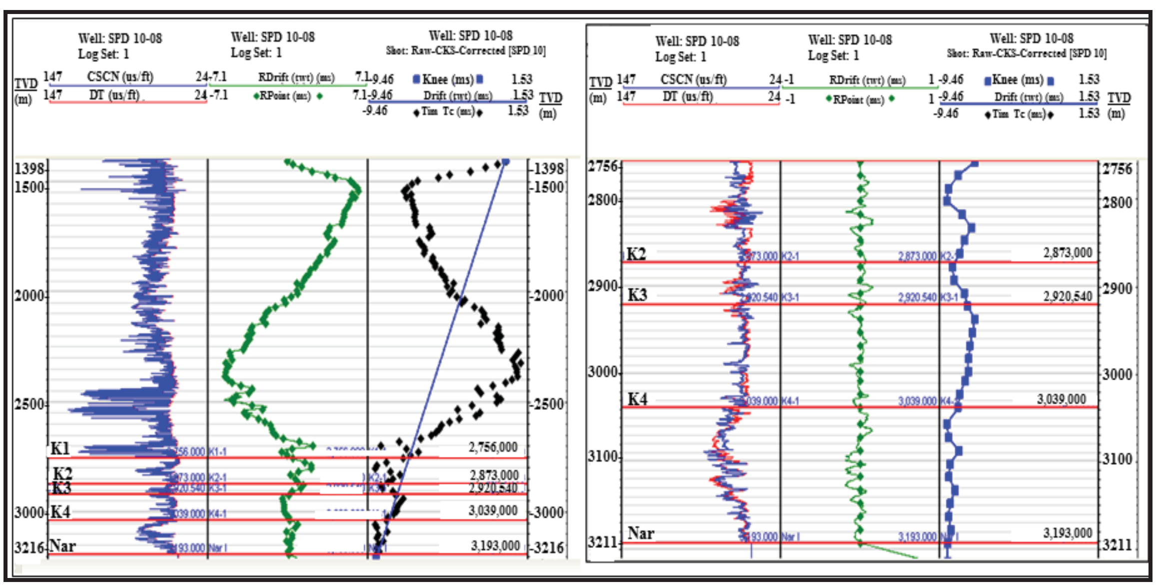

Figure 9. Sonic-check shots calibration in well SPD-10-08 before (left) and after (right) corrections.

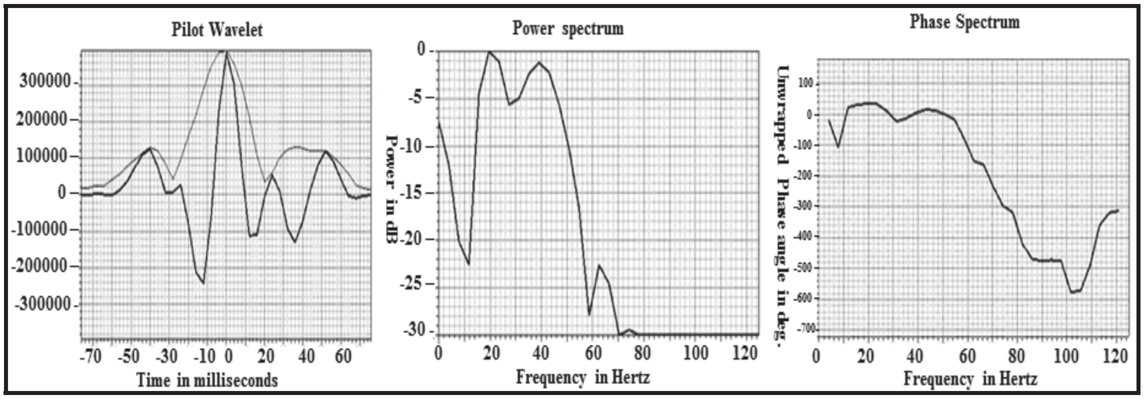

Figure 10. Extracted wavelet (left), amplitude spectrum (middle) and phase spectrum (right).

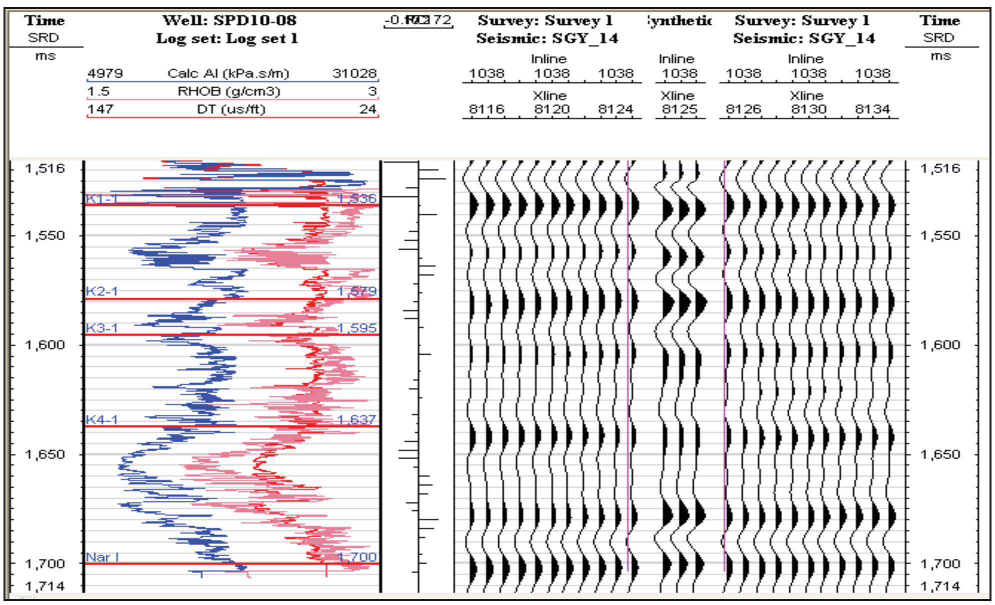

Figure 11. Synthetic seismogram using extracted wavelet and corrected check shots at well SPD-10-08.

The quality factor shows inverse relation with saturation value, i.e. the saturated rocks revealed low values of quality. However, Qp increases with lithostatic pressure and decreases with temperature. The quality low number is hydrocarbon indicator in the reservoir. Therefore, VSP method is useful tool in petroleum exploration.

VSP can present layering and rock type with / without fluids. In porous rocks, compressive and shear waves ratio, Vp/Vs, is increasing vigorously. The pores may be filled by brine, oil or gas. Resistivity log can be also used to detect the fluid type. As the low values is indicating containing water/brine while the high values are related to the presence of oil or gas in the pores. In general trend, the resistivity and density are increasing toward depth.

In the area understudy, Vp and Vs variations to depth is compared (Fig. 12). P-wave velocity increases due to hydrocarbon presence in the pores while S-wave velocity decreases in these points. Therefore, the anomalous points are correlated to the hydrocarbon potential.

In general case, when a wave is travelling through a media, it is possible to lose its geometrical amplitude, and frequency due to the environmental absorption. The absorption volume is showing in Figure 13. As the number is increasing the absorption is also increased. In seismograms the points with high amplitude marks the hydrocarbon potential correlated to petrophysical plots (Fig. 12).

The energy absorption process in porous layers is also verified and defined the hydrocarbon presence in those points. This matter is also congruent with other data (Figs. 14-15).

According to Vp and Vs plots it is observed that there are different horizons containing hydrocarbon such as 2900, 3100m. Therefore, this plot presents the hydrocarbon distribution within the reservoir. Consequently, Vp/Vs ratios and Q-factor can be applied and considered as a useful substitution of petrophysical logs to find the horizons containing hydrocarbon.

Q-factor analysis in the area under study

Quality factor was estimated for the 2700-3100m interval in the understudy well using VSP (zero offset method) from VSP data (using spectral ratio method). Density and porosity logs are also used. The dominant density is located in the range of 2.7-2.75 g/cm^2 according to colored bands. The highest porosity percentage is occurred in K4 horizon at depth of 3100m. Vp and Vs variation against to depth was plotted (Figs. 12 and 14). The lowest velocity of compressive wave is related to the depth of 3100m in K4-horizon and the highest velocity is detected at 2950m. The velocity of shear wave was also investigated in three lithologies, mudstone, limestone, and dolostone, based on concerned equations (cited above). The result data for Vs indicated that the highest velocity attributed to mudstone, the lowest velocity is in limestone and in the case of dolostone the data is located between these two limits.

In Kangan and Dalan formations the lowest and highest values of Qp are 17-2 and 25-1, respectively. Qs-data indicated that Qs value is very high for mudstone but very low for limestone. These values are presented a similarity for the range of 3050-3030m (K4 horizon).

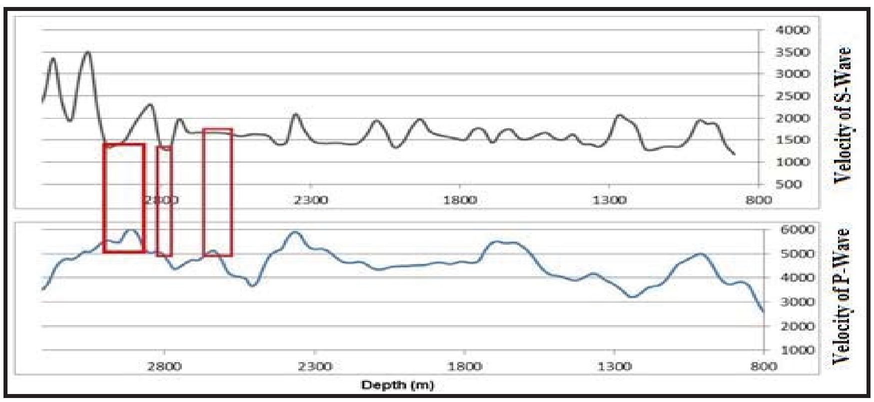

Figure 12. Vp and Vs ratio variations to depth indicating the hydrocarbon potential points (boxes).

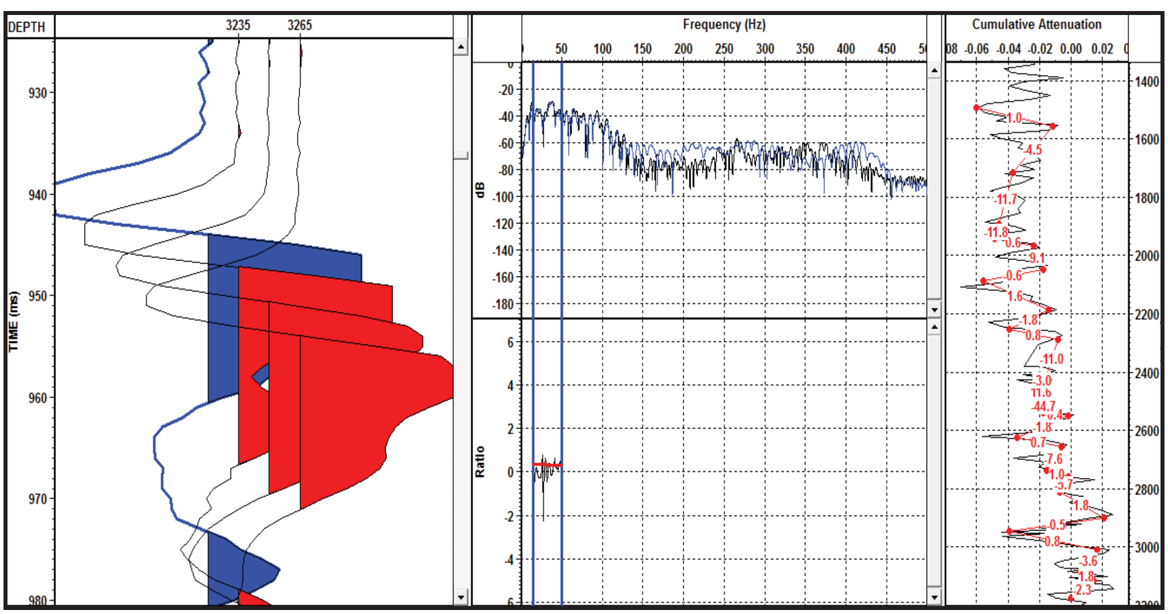

Figure 13. The absorption phenomena is presenting in layers. The numbers are per depth (right), frequency differences (middle part) of absorbed (black) and non- absorbed (blue) waves, and references waves (left).

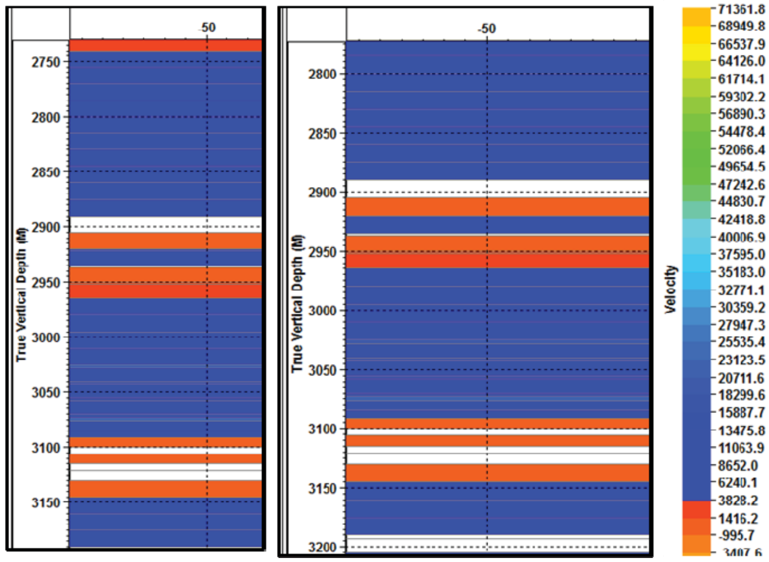

Figure 14. Velocity variation of Vp (left) and Vs (right) against to depth (m)

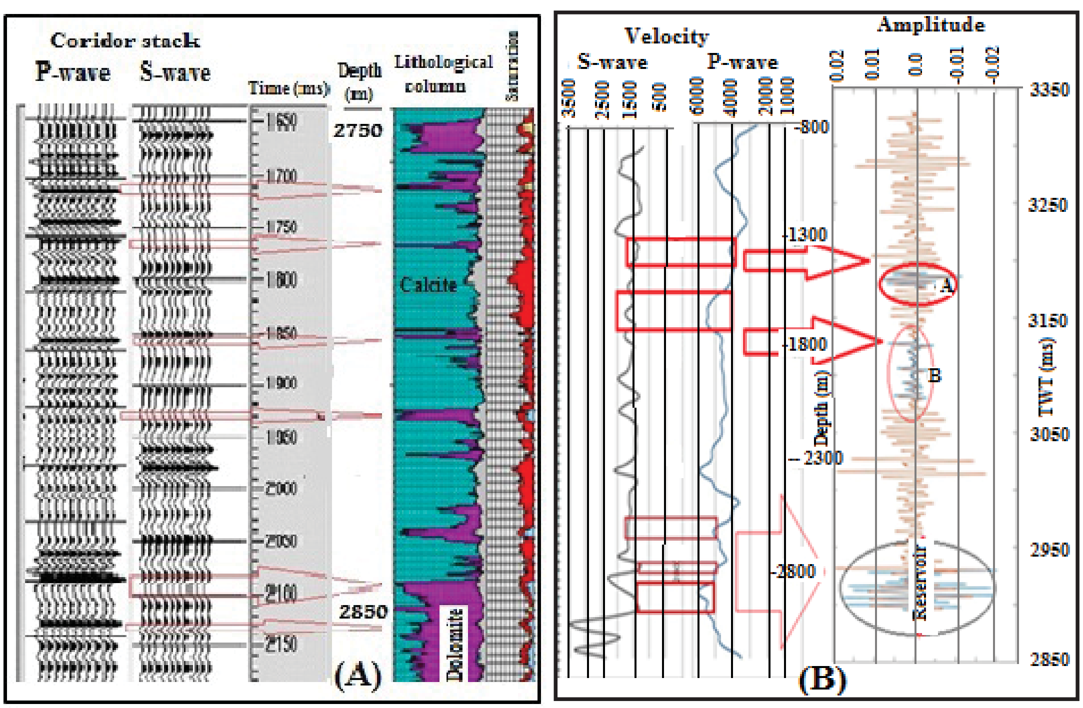

Figure 15. (A) The comparison of lithological column and corridor stack of shear and compressive waves. The consistencies of compressive wave and lithology are indicated by vectors, (B) Seismic traces are comparable to compressive and shear waves and interpreted petrophysical results. All marked sections are well correlated to the reservoir gas potential (i.e. at depths of 2700-3100, 1800, 1300m).

In the present study based on the velocity plots, Q variation to Vp/Vs ratio was also calculated. Vp/Vs ratio to depth (Fig. 14) indicated that the results of mudstone and dolostone are the same and different with the data of limestone. The Poisson ratio variation to Vp/Vs exhibited that the lowest and highest value of the Poisson is occurred within mudstone and limestone, respectively.

In gaseous zones, the Q factor values are strongly low and can be considered as an indicator of gaseous layer. The general very low estimated values of the Q-factor in this area verify the presence of gaseous hydrocarbon. It is therefore observed that Qp values and Vp/Vs ratio are correlated well and thus very low values of Qp and Qs are indicating an individual environment with high attenuation.

The comparison of lithological column and corridor stack of shear and compressive waves was shown in Figure 15. The variation of compressive wave and lithology is consistent (indicated by vectors). Seismic traces are compared to compressive and shear waves and interpreted petrophysical results. All marked sections are well correlated to each other.

Conclusions

The present research work is an attempt in offshore gas field in the Persian Gulf to detect gas accumulated zone. The results indicated that Vp/Vs and Q-factor are correlated well in this area. The hydrocarbon containing horizons proved by the logs can be determined by Vp and Vs plots. It is observed that there are different horizons in the reservoir which are containing hydrocarbon in vertical depths such as 2700, and 3100m. Therefore, these parameters can be useful to find hydrocarbon distribution through the reservoir. In any depth that the Q factor values are strongly low, it will be considered as an indicator of gaseous layer. All calculated values of this factor in this area characterize the general low values. The low values of Qp and Qs are also indicating an individual environment with high attenuation. Consequently, Vp/Vs ratios and Q-factor can be applied and considered as a useful substitution of petrophysical logs to find the hydrocarbon prone horizons.

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References

Becker, D.F., Perelberg, A.I., 1986. Seismic detection of subsurface fractures. Expanded Abstracts, 56th Ann.Int.SEG Meeting, Houston, 466–468.

Ben-Hadj-Ali, H., Operto, S., Virieux, J., 2008. Velocity model building by 3d frequency-domain, full-waveform inversion of wide-aperture seismic data. Geophysics, 73: WE101-117.

Bettinelli, P., Puech, J.C., 2015. New method of Q-factor estimation applied to optical fiber VSP data. Society of Exploration Geophysics (SEG)-2015-5800169, 015 SEG Annual Meeting, 18-23 October, New Orleans, Louisiana, 5P.

Bigdeli Tabar, M., Shams Shamsabad Farahani, S., Nikzad, M., Ghasemi Naraghi, M., 2012. A study of relations between velocity ratio and seismic quality factors ratio. J. Basic. Appl. Sci. Res., 2(1): 48-53.

Blackburn, J., Daniels, J., Dingwall, S., Hampden-Smith, G., Leaney, S., Calvez, J.L., Nutt, L., Menkiti, H., Sanchez, A., Schinelli, M., 2007. Borehole seismic surveys: Beyond the vertical profile, Oil filed Review, Autumn 2007, 20-35

Brewer, R.J., 2000. VSP Data in Comparison to Other Borehole Seismic Data, Halliburton Energy Services, Houston.

Brewer, R.J., 2002. VSP data in comparison to the check shot velocity survey, VSP Survey Meets Accuracy Demands, or “Additional Computed Product Utility, March, 2000, in AAPG Explorer, 7P.

Bulant, P., Klimeš, L., 2008. Comparison of VSP and sonic-log data in non- vertical wells in a heterogeneous structure. Geophysics, 73 (4): U19–U25.

Calderón-Macias, C., Ortiz-Osornio, M., Ramos-Martinez, J., 2004. Estimation of quality factors from converted-wave PS data: 74rd Ann. SEG Mtg., Expanded Abstracts, paper MC1.7.

Christie, P., Dodds, K., Ireson, D., Johnston, L. (S.), Rutherford, J., Schaffner, J., Smith, N., 1995. Borehole seismic data sharpen the reservoir image. Oilfield Review, Winter 1995, 18-31.

Corrigan, D., Justice, M.G., Neitzel, E.B., 1987. Estimate of shear wave anisotropy using multicomponent seismic data (abstract). Geophysics, 52:710.

Crampin, S., 1984. Evaluation of anisotropy by shear wave splitting: Applied seismic anisotropy: Theory, background, and field studies. Geophysics Reprint series, 20: 23-33.

Daley, T.M., Feighner, M.A., Majer, E.L., 2000. Monitoring underground gas storage in a fractured reservoir using time lapse VSP, Lawrence Berkeley National Laboratory Report LBNL-44876, Berkeley, CA, March, 129P.

Daley, T.M., McEvilly, T.V., Majer, E., 1988. Analysis of P and S wave vertical seismic profile data from the Salton Sea scientific drilling project. J. Geoph. Res., 93: B11, P. 13025-13036.

Dobrin, M. B., Savit, C.H., 1988. Introduction to geophysical prospecting. New York, McGraw-Hill Book Company, 300-303.

Feighner, M.A., Gritto, R., Daley, T.M., Keers, H., Majer, E.L., 1999, Three-dimensional seismic imaging of the Ryepatch geothermal reservoir, Lawrence Berkeley National Laboratory, 45P.

Haase, A.B., Stewart, R.R., 2004. Estimating seismic attenuation (Q) from VSP data at a heavy-oil field: Ross Lake,

Sask. CREWES Research Report, 16: 7P.
Haase, A.B., Stewart, R.R., 2005. Q-factor estimation. CREWES Research Report, 17: 10P
Hackert, C., Parra, J.O., 2002. Calibrating well logs to VSP attenuates, interval velocity and amplitude, The Leading Edge, 21: 52-57.
Haidar, A., 2008. On the parallel scalability of hybrid linear solvers for large 3D problems. PhD Thesis, Institut National Polytechnique de Toulouse - CERFACS TH/PA/08/57.
Haldorsen, J.B.U., Miller, D.E., Walsh, J.J., 1995. Walk-away VSP using drill noise as a source, Geophysics, 60(4): 978-997.
Hardage, B., 2000. Vertical seismic profiling. Third Edition of Handbook of Geophysical Exploration.Pergamon. 570P.
Hardage, B.A., 1983. Vertical seismic profiling-Part A: Principles, Geophysical Press, London,
He, R., Hornby, B., and G. Schuster (2006) 3D wave-equation interferometric migration of VSP multiples, SEG/New Orleans 2006 Annual Meeting, P.3442-3446.
Hinds, R., Anderson, N., Kuzmiski, R., 2002. VSP interpretative processing: Theory and practice. SEG open file publications No.3.
Kearey, P., Brooks, M., Hill, I., 2002. An introduction to geophysical exploration. Blackwell Publishing.
Keehn, N.A., Kanasewich, E.R., 1987. Attenuation from VSP data collected on Mellville Island. J. Canad. Soci. EXPL. Geoph. 23 (1): 73-84.
Kennett, P., Ireson, R.L., Conn, P.J., 1980. Vertical seismic profiles: Their applications in exploration geophysics. Geophys. Prospecting, 28: 676- 699.
Koskulics, J., Englehardt, S., Long, S., Hu, Y., Stamnes, K., 2012. Method of surface topography retrieval by direct solution of sparse weighted seminormal equations. Optic Express, 20 (2): 1714-1726.
Kreona, A., 2012. Processing and analysis of Vertical Seismic Profile data acquired while drilling (VSP-WD). Master's thesis in Petroleum Geosciences engineering, University of Stavanger, Norway.
Kumar, G.; Batzle, M., Hofmann, R., 2003. Effect of fluids on attenuation of elastic waves. 73rd Ann. Internat. Mtg. Soc. of Expl.Geophys, 1592-1595.
Li, F., Zhou, H., Jiang, N., Bi, J., Marfurt, K. J., 2015. Q estimation from reflection seismic data for hydrocarbon detection using a modified frequency shift method. Journal of Geophysics and Engineering, 12 (4): 577- 586, doi: 10.1088/1742-2132/12/4/577.
Lorenzo, C., Soto, J., Palma, H., Diez, H., Pérez, H., 2015. Vertical seismic profile (VSP) in injection well AZ- 03, Los Azufres geothermal field, México. Proceedings World Geothermal Congress, Melbourne, Australia, 19- 25 April, 10P.
Majer, E. L., McEvilly, T. V., Eastwood, F., Myer, L., 1988. Fracture detection using P-wave and S-wave vertical seismic profiling at the Geysers. Geophysics, 53: 76-84.
Marques, J.J., Novelino, V., Guerra, R., Galaguza, M., Costa, M., 2011. VSP survey assists in the reservoir characterization of deep – water turbiditic reservoir offshore Brazil. 12th International Congress of the Brazilian Geophysical Society, SBGF, 4P.
Milkereit, B., Adam, E., Li, z., Qian, W., Bohlen, T., Banerjee, D., Schmitt, D.R., 2005. Multi-offset vertical seismic profiling: an experiment to assess petrophysical-scale parameters at the JAPEX/JNOC/GSC et al. Mallik 5L-38 gas hydrate production research well. in: Scientific results from the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada , edited by S. R. Dallimore and T. S. Collett, Bull. Geol. Surv. Can. 585, 13 pp.
Milsom, J., 2003. Field Geohysics. Third edition John Wiley & Sons Ltd. University College London. England.
Miong, S.K., Stewart, R.R., Wong, G., 2007. Shallow VSP for near-surface structure and statics, extended abstract prepared in conjunction with a presentation given at CSPG/CSEG 2007 Geo Convention, Calgary, AB, Canada, May 14-17, 7P.
Mohamed, A.R.S., Susilo, A., Maryanto, S., 2013. Analysis of zero offset vertical seismic profiling data processing to evaluate the oil and gas reservoir in Well "X", Murzuk Basin, Soutwest Libya. International Refereed Journal of Engineering and Science (IRJES), 2 (11): 19-29.
Mokhtari, M., Pourhossein, H., 2003. Significance of VSP data for surface seismic data; south Ghashu Gas Field, South Iran. Iranian Int. J. Sci., 4(2): 223-240.
Moore, G.F., Shipley, T.H., Stoffa, P.L., Karig, D.E., Taira, A., Kuramoto, S., Tokuyama, H., Suyehiro, K., 1990. Structure of the Nankai Trough accretionary zone from multichannel seismic reflection data. J. Geophys. Res., 95: 8753- 8765.
Moore, G.F., Zhao, Z., Shipley, T.H., 1997. Integration of vertical seismic profiling, logging, and seismic data in the vicinity of the decollement, Northern Barbados ridge accretionary prism, Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 156.
Nazarchuk, Z., Skalskyi, V., and Serhiyenko, O., 2017. Acoustic Emission, Foundations of Engineering Mechanics, Springer International Publishing AG. 283P. DOI 10.1007/978-3-319-49350-3.

Nichols, J., Mikesell, D., van Wijk, K., 2010. Application of the virtual refraction to near-surface characterization at the Boise Hydrogeophysical Research Site. European Association of Geoscientists & Engineers (EAGE), extended abstract presented in 71th EAGE Conference & Exhibition Incorporating SPE EU-ROPEC 2009, 8–11 June 2009 in Amsterdam, Geophysical Prospecting, P. 1–11

Nihei, K. T., Li, X., 2007. Frequency response modelling of seismic waves using finite difference time domain with phase sensitive detection (TD-PSD). Geophysical Journal International, 169: 1069-1078.

Oliveira, F.S., Figueiredo, J.S., Oliveira, A.G., 2015. Quality factor estimation based on the frequency shift method and re-datuming operator: Application on real dataset, 2015 SEG Annual Meeting, 18-23 October, New Orleans, Louisiana, SEG-2015-5905344, 6P.

Oristaglio, L., 1985. A guide to the current uses of vertical seismic profiles. Geophysics, 50: 2473-2479.

Plessix, R. E., 2009. Three-dimensional frequency-domain full-waveform inversion with an iterative solver. Geophysics, 74: WCC149-WCC157.

Pride, S. R., Berryman, J.C., Harris, J.M., 2004. Seismic attenuation due to wave-induced flow. J. Geophys. Res., 109: B0120l, 19P.

Pride, S.R., Berryman, J.G., 2003. Linear Dynamics of Double-Porosity Dual Permeability Materials II, Fluid Transport Equations. Phys. Rev. E., 68: 036604.

Quan, Y., Harris, J. M., 1997. Seismic attenuation tomography using the frequency shift method. Geophysics, 62 (3): 895-905.

Richardson, S.E., Lawton, D.C., 2003. Zero-offset vertical seismic profiles of coalbed methane strata: a comparison of three vibrating sources. CREWES Research Report, 15: 12P.

Sakai, A., 1999. Velocity analysis of vertical seismic profile (VSP) survey at JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, and related problems for estimating gas hydrate concentration, in Scientific Results from APEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, edited by S. R. Dallimore, T. Uchida, and T. S. Collett, Bull. Geol. Surv. Can. 544 , 323– 340.

Samieh, J., Ghasem Al Askari, M.K., 2010. Estimation of seismic quality factor using VSP data. J. of the Earth, winter, 4 (4): 67-75.

Schlumberger (2014) Diagram of VSP configurations, Retrieved 4 August 2014.

Schuster, G. T., Followill, F., Katz, L.J., Yu, J., Liu, Z., 2004. Autocorrelo- gram migration: Theory. Geophysics, 68: 1685–1694.

Sengel, E.W., 1981. Handbook on well logging. Oklahoma City, Oklahoma: Institute for Energy Development. 168 p. ISBN 0-89419-112-8.

Sheriff, R. E., Geldart, L.P., 2002. Encyclopedia dictionary of applied geophysics. Fourth Edition Geophysical References series, 13: 429P. DOI: 10.1190/1.9781560801979.

Shipley, T.H., Moore, G.F., 1986. Sediment accretion, subduction, and dewatering at the base of the trench slope off Costa Rica: A seismic reflection view of the décollement. J. Geophys. Res., 91: 2019- 2028.

Shipley, T.H., Moore, G.F., Bangs, N.L., Moore, J.C., Stoffa, P.L., 1994. Seismically inferred dilatancy distribution, northern Barbados Ridge décollement: implications for fluid migration and fault strength. Geology, 22: 411- 414.

Sirgue, L., Etgen, J. T., Albertin, U., 2008. 3D Frequency Domain Waveform Inversion using Time Domain Finite Di_erence Methods. In: Proceedings 70th EAGE, Conference and Exhibition, Roma, Italy, F022.

Smithyman, B.R., Peters, B., Herrmann, F.J., 2015. Constrained waveform inversion of colocated VSP and surface seismic data, 77th EAGE Conference & Exhibition, IFEMA Conference, Madrid, 1-4 June, 5P.

Society of Professional Well Log Analysts, 1975. Glossary of terms & expressions used in well logging. Houston, Texas: SPWLA, 74 p.

Sourbier, F., Haiddar, A., Giraud, L., Ben-Hadj-Ali, H., Operto, S., Virieux, J., 2011. Three-dimensional parallel frequency-domain visco-acoustic wave modeling based on a hybrid direct/iterative solver. Geophysical Prospecting, 59(5): 834-856.

Stewart, R.R., Huddleston, P.D., Tze Kong, K., 1984. Seismic versus sonic velocities: A vertical seismic profiling study. Geophysics, 49: 1153-1168.

Trice, R., 2014. Basement exploration, West of Shetlands: progress in opening a new play on the UKCS. Geological Society, London, Special Publications, 397: 81-105.

Uyanik, O., 2010. Compressional and shear-wave velocity measurements in unconsolidated top-soil and comparison of the results. International Journal of the Physical Sciences, 5 (7): 1034-1039.

Vasconcelos, I., Snieder, R., Hornby, B., 2008. Imaging internal multiples from subsalt VSP data — Examples of target-oriented interferometry. Geophysics, 73 (4): S157–S168.

Westbrook, G.K., 1991. Geophysical evidence for the role of fluids in accretionary wedge tectonics. Phil Trans. R. Soc. Lond. A, 335: 227- 242.

Winkler, K. W., Nur, A., 1982. Seismic attenuation - Effects of pore fluids and frictional sliding. Geophysics, 47: 1–15.

Wu, B., Lawton, D.C., Hall, K.W., 2015. Analysis of multicomponent walkaway vertical seismic profile data, Geo Convention, 4-8 May 2015, Calgary, Canada, 4P.

Yang, C., 2010. Time-lapse analysis of borehole and surface seismic data, and reservoir characterization of the Ketzin CO_2 storage site, Germany. PhD Thesis, Uppsala University, 72P.

Zhang, C., Ulrych, T. J., 2002. Estimation of quality factors from CMP records. Geophysics, 67: 1542–1547, doi: 10.1190/1.1512799.

Zhang, Z., 2010. Assessing attenuation, fractures, and anisotropy using logs, vertical seismic profile, and three-component seismic data: heavy oilfield and potash mining examples. PhD Thesis, Department of Geoscience, Calgary, Alberta, Canada, 234P.

Zhang, Z., Stwart, R., 2007. VSP Analysis at the Ross Lake Oilfield, Saskatchewan. CSPG CSEG Convention.

Zhao, Y., Li, Z., Nie, Y., 2016. A Time-Frequency Analysis Method for Low Frequency Oscillation Signals Using Resonance-Based Sparse Signal Decomposition and a Frequency Slice Wavelet Transform. Energies, 9, (151): 18P. Doi: 10.3390/en9030151,

Zimmerman, L. J., Chen, S.T., 1993. Comparison of vertical seismic profiling techniques. Geophysics, 58 (1): 134-140.