ESTIMATION OF SEISMIC ATTENUATION IN THE KANGAN FORMATION FROM WALKAWAY VSP DATA

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ABSTRACT

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In this paper we use the geometry of walkaway vertical seismic profiling (WVSP) in order to define seismic wave attenuation trends in the Kangan reservoir sequences of the South Pars oil field. The mean relative-amplitude attenuation values are analyzed as a function of geophone-source offsets. Our purpose is determining locations in which attenuation shows excessive amounts, that would indicate the possibility if there was any location where there was excessive energy attenuation, that would indicate the possibility of an overpressure zone that would be a drilling hazard. The amplitudes in one walkaway VSP survey line were evaluated to observe any main variation of amplitude in different offsets and to estimate the attenuation of seismic waves energy. Downgoing first arrivals were separated by applying a time window after flattening along a targeted horizon and then performing Fast Fourier Transform (FFT) on first arrivals.

In WVSP data acquisition, seismic waves propagate through the geological layers via different source-receiver offsets to reach a constant-geophone depth in subsurface. By processing the amplitudes of these waves, The amounts of attenuation is measured and the lost energy is estimated.

KEY WORDS: walkaway VSP, seismic wave attenuation, seismic quality factor,
Q-estimation, South Pars.

INTRODUCTION

Seismic wave energy attenuates as the wave propagates downward into the earth. Seismic wave attenuation could be due to different facts such as geometric dispersion, absorption and the loss of reflection and transmission. Attenuation estimates are important for recognizing lithology changes or estimating fluid content (Rapoport and Ryjkov, 1994; Martin et al., 1998).

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Several different methods have been used to estimate rock absorption variables. The classic spectrum ratio (Hauge, 1981; Toksöz and Johnston, 1981; Jannsen et al., 1985; Tonn, 1991) was employed in this study and the spectrum-modelling method is a modified approach to the spectral-ratio method but does not involve division of spectra, when correct amplitudes are not accessible, spectral modelling is the best-fit method. The match-filter method and the match-technique method (Raikes and White, 1984; Tonn, 1991) use the notion of matching at different steps of Q-estimation methods. The analytic signal method (Engelhard, 1996) evaluates quality factor Q in the time domain by using a linear relationship between the logarithm of the instantaneous frequency ratio before and after attenuation and the average instantaneous frequency.

Extraction of seismic wave attenuation values from VSP data is done by measuring the changes in amplitude values of compressional *P*-wave first arrivals corresponding to direct travel paths from source to receiver positions. Our attenuation analysis follows that of Hauge (1981) but considers various offsets instead of different depths.

This WVSP experiment was done in a nominally vertical well in South-Pars, Offshore Iran. The total depth range covered in the walkaway VSP was 2535-2670 m MD below sea floor with geophone interval spacing of 15 m. The first geophone positioned at 2669.79 m and the second geophone at 2654.67 m, the third geophone at 2639.55 m, the fourth geophone at 2624.43 m and the fifth geophone located at 2609.31 m. The seismic sources consisted of a Sleeve Gun-IIB fired 6 m below the mean sea level, i.e., the reference datum. The ASI (Array Seismic Imager) downhole receiver was developed for acquiring 5-level, 3-axis, simultaneous data in cased holes. The tool consists of a string of five equally spaced sensor packages below a set of cartridges. The principal advantage of using an array-type tool over a conventional single-level tool is operational efficiency in acquiring borehole seismic data.

THEORY

The spectral ratio technique (Hauge, 1981; Toksöz and Johnston, 1981) is commonly used for Q-value approximation of VSP data. For downgoing waves $g_1(t)$ and $g_2(t)$ recorded at depths Z_1 and Z_2 (Hardage, 2000)

$$G_2(f) = kG_1(f)e^{-\alpha f} \tag{1}$$

where $G(f)$ is the amplitude spectrum, f is the frequency, and k is a frequency independent feature that is used for amplitude effects such as spherical divergence, variations in recording gain, and changes in source and receiver coupling. The exponent, α, is the cumulative seismic wave attenuation between depths Z_1 and Z_2, and it is also assumed to be independent of frequency. This equation can be rewritten as the following equations which Q is seismic wave quality factor λ is seismic wave length, R is the reflection coefficient and G is the geometrical spreading factor.

$$\ln\left[\frac{G_2(f)}{G_1(f)}\right] = -\alpha f + \ln(k) \quad , \tag{2}$$

$$\alpha = \frac{\pi}{Q\lambda} \quad , \tag{3}$$

$$K = R.G \quad . \tag{4}$$

The left side of eq. (2) is the spectral ratio of the two VSP outputs recorded at Z_1 and Z_2, respectively. The cumulative attenuation value is determined by the slope of the best line fitting to this spectral ratio trend (Zhang and Stewart, 2007).

THE SOUTH PARS FIELD

The South Pars field is assumed to be the world's largest natural-gas condensate field. It is located on the border line of Iran and Qatar in the Persian Gulf, Middle East area. The South Pars field (3700 square kilometers) in Iranian water is part of the north trending South Pars-Qatar Arch structural region. The zone is a major anticline that extends along the center of Persian Gulf and warps of the Phanerozoic sedimentary succession of the Arabian Platform (Perotti et al., 2011). The structure has a northeast–southwest direction and is bounded on the north by the Zagros fold (Northwest-Southeast) and thrust belt (North and Northeast) (Aalia et al., 2006) and spreads south into Qatar.

The development of the South Pars happens in several ages of time, Alsharan and Nairn (1994) state the structure began at the end of the Triassic to Early Jurassic, and during the Turonian, the Premature-Middle Eocene, terminated in Middle Eocene. The Late Eocene to Oligocene was a key phase of South Pars Arch uplift that produced a major unconformity. Another uplift phase started in the Early Miocene and continued into the Late Miocene–Pliocene (Perotti et al., 2011).

There is no available subsurface control (either well or seismic) for the basement below the South Pars-Qatar Arch and nearby parts in the

Persian Gulf. As far as basement complexity has been investigated, the top of basement high lies below the Qatar cape, as shown by the tentative basement map drawn by Konert et al. (2001), and is located at a depth of 4-5 km. Depth of basement rapidly increases to 8-9 km in the western part of the Persian Gulf, as well as to the north and east of Qatar. The thickness of the sedimentary cover in the Persian Gulf has been generally quoted by other authors as being more than 10 km, 12 km (Pollastro, 2003) or 13 km (Edgell, 1996; Perotti et al., 2011)

The gross pay zone in the South Pars is approximately 450 m thick, extending from depths of approximately 2750 to 3200 m. Reservoir dip is gently toward the NE. The average thickness of the reservoir units is 450 (m) in South Pars to 385 (m) in North Field. As in other reservoir configurations in adjacent areas, the reservoir in the Qatar Arch is cut by a set of NNW-SSE faults (Rahimpour-Bonab et al., 2010).

In the field, gas development is mostly from Permian-Triassic units. Kangan–Dalan formations form natural gas reservoirs. The Persian Gulf is composed of carbonate–evaporate series known as the Khuff formation (Aalia et al., 2006).

Permian-Early Triassic has been separated into Faraghan (Early Permian), Dalan (Late Permian) and Kangan (Early Triassic) Formations (Aalia, et al. 2006). The Khuff Formation in the Persian Gulf region is predominantly a shallow marine carbonate series of late Permian age, formed during transgressive-regressive depositional cycles. It diverges considerably in thickness (from 500 to 975 m) and in reservoir quality. The formation proved the presence of large volumes of gas in Saudi Arabia, Bahrain, Qatar, Iran and United Arab Emirates and minor oil in Saudi and Omani fields. It is assumed that porosity and permeability are both low values, but may be enhanced by a system of open fractures, which makes the Khuff sequence a good to very good reservoir. The source of the gas is either from Silurian shales or is indigenous to the Khuff carbonate itself. The anhydritic shale of the Lower Triassic Sudair Formation forms an excellent seal.

The South Pars field contains two main independent gas-bearing formations, Kangan (Triassic) and Dalan (Permian) in a carbonate-evaporate series known as the Khuff Formation. Each formation is segregated into two dissimilar reservoir layers, separated by impermeable barriers. The field has four independent reservoir layers K1, K2, K3, and K4 (Bordenave, 2003).

The K1 and K3 units are mainly composed of dolomites and anhydrites while K2 and K4, which constitute major gas reservoirs, are composed of limestone and dolomite. A massive anhydrite (the Nar

Member) separates the K4 from the underlying K5 unit, which has poor reservoir qualities (Rahimpour-Bonab et al., 2010). These units are also discussed in other literatures in onshore part of the study area (Shahrabi et al., 2016).

Methodology for estimation of absorption

The downgoing P-wave of WVSP vertical component data was used in processing for attenuation estimation (Figs. 1 and 3). The first step in processing was to apply a first break time shift to all the traces to flatten the onset peaks to 100 ms (Figs. 2 and 4) and then, separate downgoing waves from upgoing waves by median filtering (Fig. 4). Attenuation measurements were made using the first pulse arrivals of each trace. Data in interval of 80-120 ms were separated using a cosine-tapered window (Fig. 5).

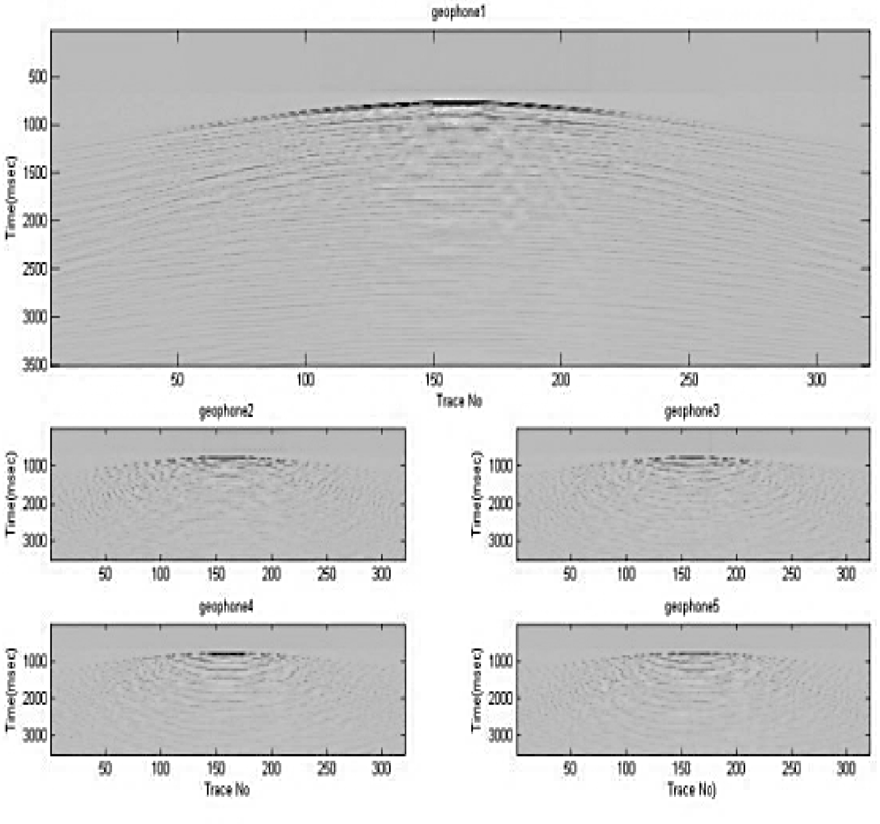


Fig. 1. Raw WVSP vertical component data.

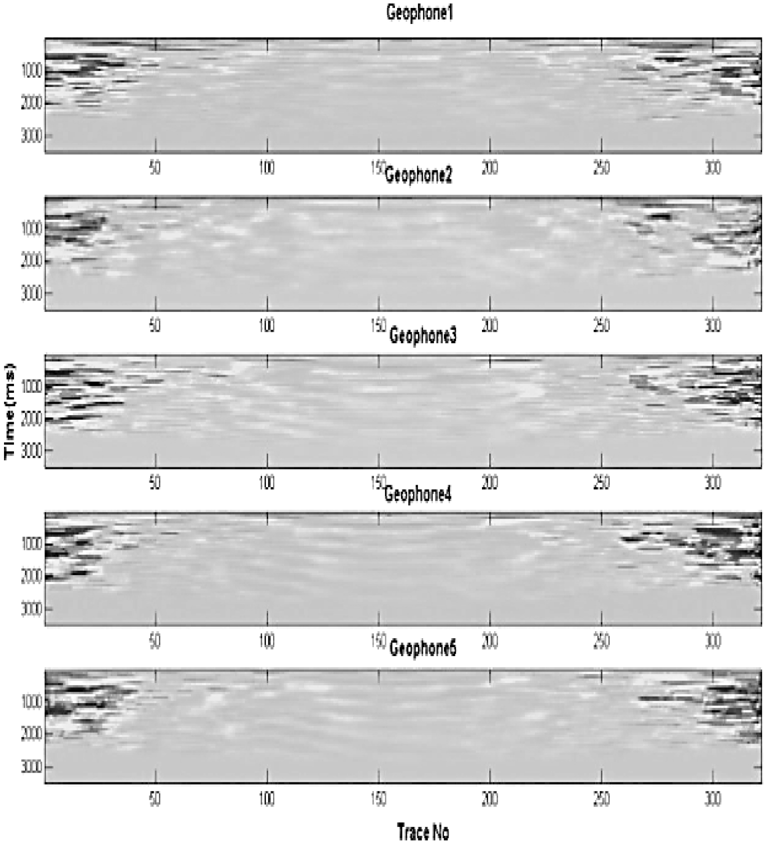


Fig. 2. Raw WVSP vertical component flattened data.

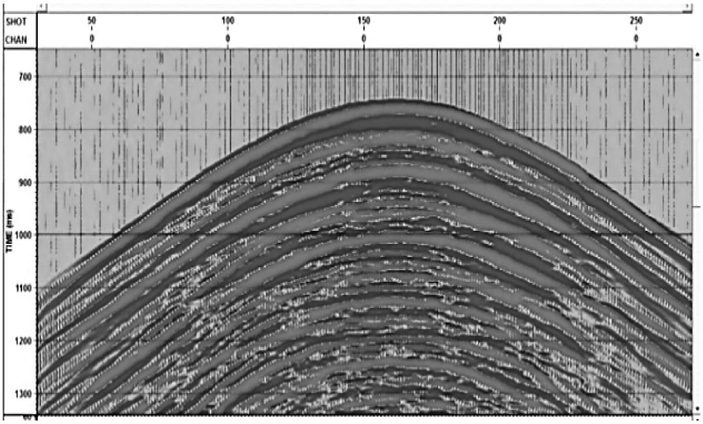


Fig. 3. Geophone 1, WVSP vertical component (depth = 2655-2670 m).

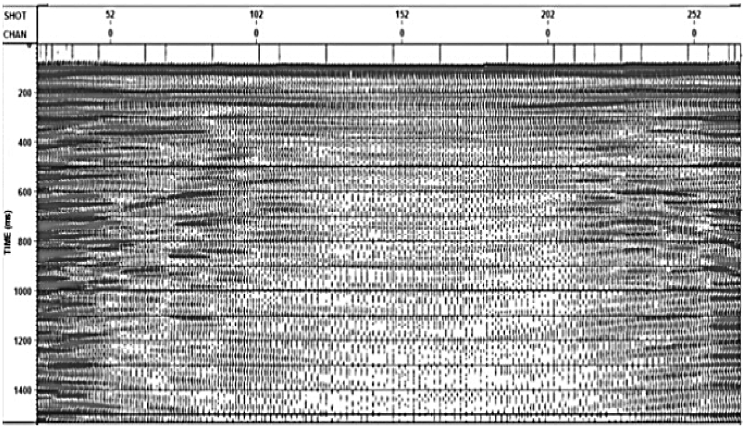


Fig. 4. Geophone 1, WVSP vertical component downgoing wave.

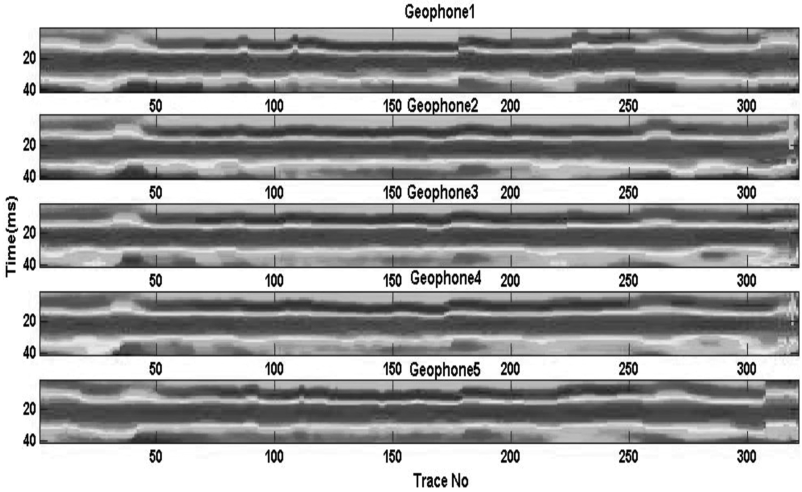


Fig. 5. Five geophone first arrival in a targeted 80-120 ms window.

Including the tapered portions to zero, the windowed first arrivals correspond to 321 sample series, each of which was fast Fourier transformed to compute the amplitude spectra (Fig. 6). Due to low qualities of data, spectral ratios were computed only the frequency band 5 to 55 Hz. The signal to-noise ratio over this band ranged from 20 dB to 40 dB. Offset instead of depth, as reference seismogram used in calculating spectral ratios. A least-squares slope is fitted to each spectral ratio (Fig. 7), and the resultant cumulative attenuation values are plotted versus offset (Fig. 8).

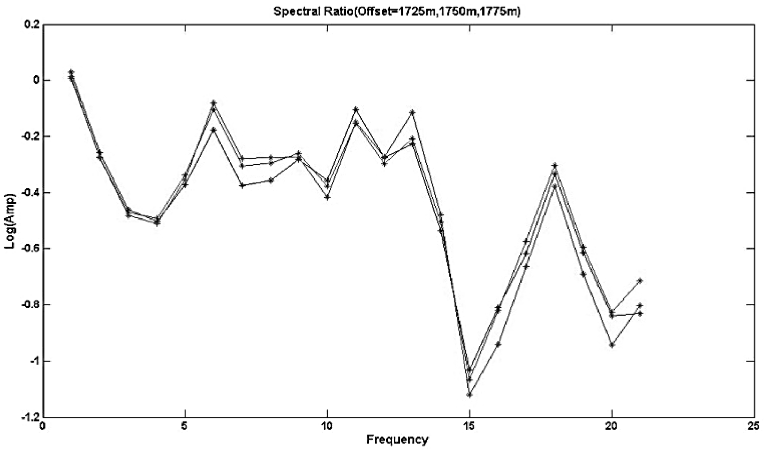
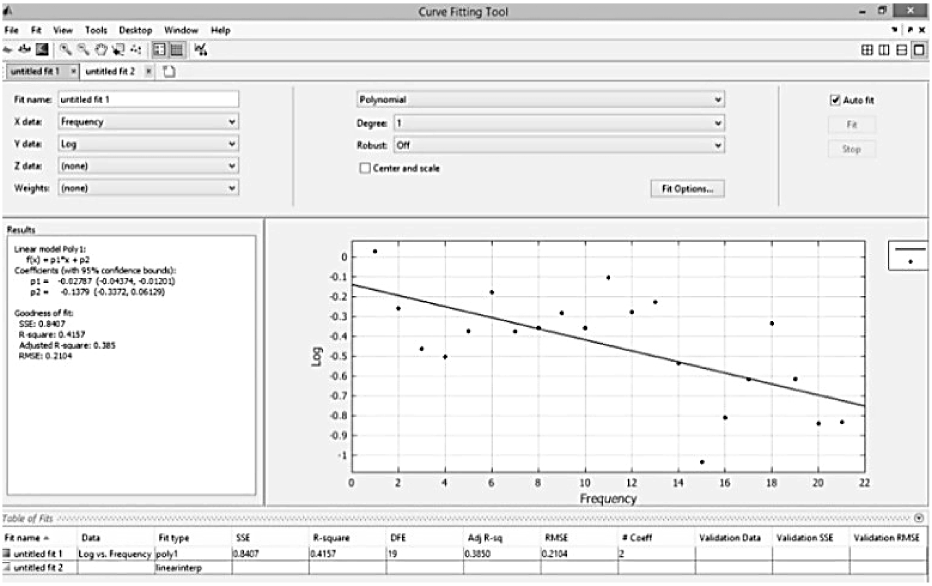


Fig. 6. Spectral ratio (offset = 1725 m, 1750 m, 1775 m).



Fit name: untitled fit 1
X data: Frequency
Y data: Log
Z data: (none)
Weights: (none)

Polynomial
Degree: 1
Robust: Off
☐ Center and scale

```
Linear model Poly 1:
    f(x) = p1*x + p2
Coefficients (with 95% confidence bounds):
      p1 =   -0.02787  (-0.04374, -0.01201)
      p2 =    -0.1379  (-0.3372, 0.06129)

Goodness of fit:
  SSE: 0.8407
  R-square: 0.4157
  Adjusted R-square: 0.385
  RMSE: 0.2104
```

Fit name ▲	Data	Fit type	SSE	R-square	DFE	Adj R-sq	RMSE	# Coeff	Validation Data	Validation SSE	Validation RMSE
untitled fit 1	Log vs. Frequency	poly1	0.8407	0.4157	19	0.3850	0.2104	2			
untitled fit 2		linearinterp									

Fig. 7. Straight line fitting to the spectral ratios using Matlab CFTool.
(Offset = 1725, RMS = 0.21, Slope = -0.02787, Intercept = -0.1379).

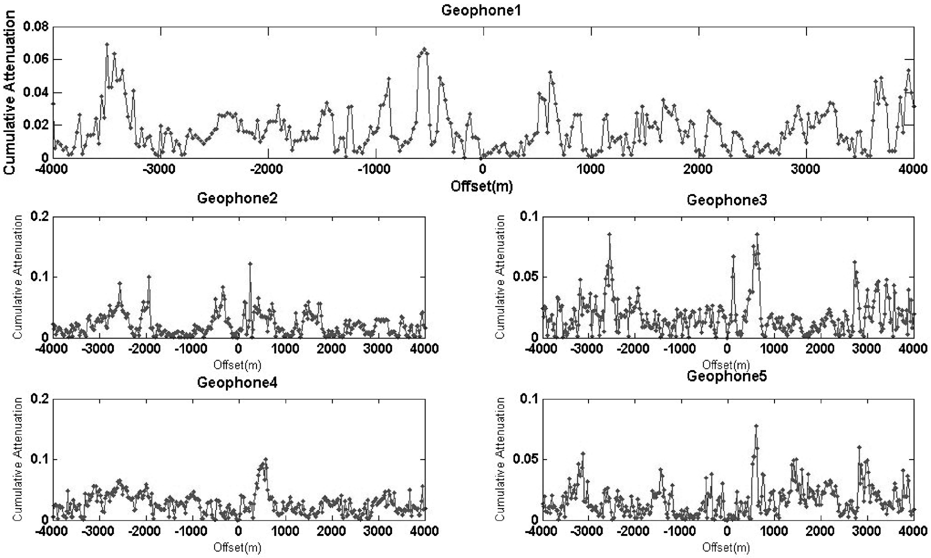


Fig. 8. Cumulative attenuation vs. offset.

CONCLUSION

The idea proposed in this paper is a type of spectral ratio method for Q-estimation that uses first arrival P-wavelets in walkaway VSP data acqurues at an Iranian oil field. Our purpose was to investigate seismic wave attenuation in different horizon zones. Our objective was to look for any geological variation in layers by moving our analysis along horizontal offsets.

It is investigated that at a constant depth, attenuation of seismic wave is increasing by offset as expected. Low quality of data in some offsets caused some distortion in attenuation trends.

We show that at 5 different geophone depths, cumulative attenuation values versus offsets was fixed, i.e., no obvious major fluctuations in P-Energy attenuation as offset data was analyzed at different geophone depths. This finding indicates that there is not any over pressure drilling risk for production purposes. We conclude that lithology does not vary widely to change P-wave amplitude. By considering other geological reports and local studies, we conclude that the Kangan formation is a non-porous and non-permeable cap rock.

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REFERENCES

Aalia, J., Rahimpour-Bonaba, H. and Kamali, M.R., 2006. Geochemistry and origin of the world's largest gas field from Persian Gulf, Iran. J. Petrol. Sci. Engineer., 50: 161-175.

Alsharhan, A.S. and Nairn, A.E.M., 1994. Geology and hydrocarbon habitat in the Arabian Basin: The Mesozoic of the State of Qatar. Geol. Mijnb., 72: 264-295.

Bordenave, M.L., 2003. Gas prospective areas in the Zagros domain of Iran and in the Gulf Iranian waters. Abstr., AAPG Ann. Mtg., Houston.

Edgell, H.S., 1996. Salt tectonism in the Persian Gulf basin. Geological Society, London, Special Publications, 100: 129-151.

Engelhard, L., 1996. Determination of seismic wave attenuation by complex trace analysis, Geophys. J. Internat., 125: 608-622. doi:10.1111/j.1365-246X.1996.tb00023.x.

Hardage, B., 2000. Vertical Seismic Profiling. 3rd updated and revised ed. Pergamon Press, Oxford.

Hauge, P.S., 1981. Measurements of attenuation from vertical seismic profiles. Geophysics, 46: 1548-1558.

Jannsen, D,. Voss, J. and Theilen, F., 1985, Comparison of methods to determine Q in shallow marine sediments from vertical reflection seismograms. Geophys. Prosp., 23: 479-497.

Konert, G., Afifi, A.M., Al-Hajri, S.A. and Droste, H.J., 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate. GeoArabia, 6: 407-442.

Martin, N., Azabche, A. and Donati, M., 1998. Indirect oil detection by using P-wave attenuation analysis in eastern Venezuela basin. Expanded Abstr., 68th Ann. Internat. SEG Mtg., New Orleans.

Perotti, C.R., Carruba, S., Rinaldi, M., Bertozzi, G., Feltre, L. and Rahimi, M., 2011. The Qatar-South Fars arch development (Arabian Platform, Persian Gulf): insights from seismic interpretation and analogue modelling. In: New Frontiers in Tectonic Research-At the Midst of Plate Convergence.

Pollastro, R.M., 2003. Total petroleum systems of the Paleozoic and Jurassic, Greater Ghawar Uplift and adjoining provinces of central Saudi Arabia and northern Arabian-Persian Gulf (pp. 2202-H). US Dept. Inter., US Geol. Surv.

Rahimpour-Bonab, H., Esrafili-Dizaji, B. and Tavakoli, V., 2010. Dolomitation and anhydrite precipitation in Permo-Triasic carbonate at the South Pars gasfield, offshore Iran: Controls on reservoir quality. J. Petrol. Geol., 33: 43-66.

Raikes, S.A. and White, R.E., 1984. Measurements of earth attenuation from downhole and surface seismic recordings. Geophys. Prosp., 32: 892-919.

Rapoport, M. and Ryjkov, V., 1994. Seismic waves velocity dispersion: an indicator of hydrocarbons. Expanded Abstr., 64th Ann. Internat. SEG Mtg., Los Angeles: 94.

Shahrabi, M.A., Hashemi, H. and Hafizi, M.K., 2016. Application of mixture of Gaussian clustering on joint facies interpretation of seismic and magnetotelluric sections. Pure Appl. Geophys., 173: 623-636.

Toksöz, M.N. and Johnston, D.H., 1981. Seismic Wave Attenuation. Geophysics Reprints Series, SEG, Tulsa, OK.

Tonn, R., 1991. The determination of the seismic quality factor Q from VSP data: a comparison of different computational methods. Geophys. Prosp., 39: 1-27.

Zhang, Z. and Stewart, R.R., 2007. Seismic attenuation and rock property analysis in a heavy oilfield: Ross Lake, Saskatcehwan. CREWES Res. Rep., 19.