Pre-stack quantification of gas-hydrate resources using simulated annealing optimization and rock physics modeling

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ABSTRACT

The method of amplitude variation with angle (AVA) inversion was applied to estimate hydrate and gas saturations along a bottom simulating reflector (BSR) at the Makran Accretionary Prism, Iran. Three AVA approximations were used and their corresponding AVA attributes were compared to each other. v_S/v_P values are usually unknown for unexplored regions and here a simulated annealing approach was taken to derive the v_S/v_P in a number of locations. These values were then interpolated to get an estimation of v_S/v_P for other locations.

Quantification of hydrate and gas saturations was based on a correlation between the AVA inverted attributes and the rock physics derived attributes (RPDA). Corresponding saturations of the nearest RPDA to a pair of AVA inverted attributes were considered as the hydrate and gas saturation for that specific location. The quantification assessment indicated 11%, 14% and 15% hydrate saturations in the vicinity of the BSR for locations with low, intermediate and high post-stacked amplitude, respectively. The saturation of the free gas was also estimated as < 1%, 2% and 3% with the same order as above, respectively.

Key words: gas hydrate, AVA inversion, BSR, Makran Accretionary Prism

INTRODUCTION

Gas hydrate resources are considered as a promising source of energy due to their widespread occurrence and also their vast quantities of gas content (mainly methane). Exploration of these resources has been highly motivated by recent advances in the exploitation of hydrates from deep-sea reserves. A concentration of gas hydrate that is thought to occur at a specific location and its main characteristics and quantity are estimated from indirect methods is categorized as an inferred gas hydrate resource (Milkov and Sassen, 2002). Also, accumulations that have been directly sampled at least in one location are categorized as indicated resources. Inferred and indicated hydrate accumulations occur at about 70 continental margin regions worldwide. Seismic analyses have an important role in the assessment of hydrate resources in these regions, whereas direct measurements (e.g. well information) are rare or absent.

METHODOLOGY

AVA INVERSION

The AVA scope of application has grown to include hydrate resource characterization and some authors have represented AVA hydrate resource assessments (e.g. Andreassen et al., 1997). In the current study, the AVA inversion based on approximations by Shuey (1985), Smith and Gidlow (1987) and Fatti et al., (1994) were applied to the seismic data from the Makran Accretionary Prism, Iran. All of three equations are the modifications of Aki and Richards approximation (1980, P. 153) as follow:

Shuey's approximation (1985): their equation was arranged in such way that each term contributes in a different angular (making a limited angle assumption in which the third term was dropped):

$$R \approx I + G\sin^2\theta, \quad (1)$$

where,

$I = ½[\Delta v_P/v_P+\Delta\rho/\rho]$, $G = ½[\Delta v_P/v_P]-4\gamma[\Delta v_S/v_S]-2\gamma[\Delta\rho/\rho]$.

The first term is the intercept which measures the reflection amplitudes at normal incidence. The second is the gradient and predominate at the intermediate which measures the variation rate of P-wave reflection with increasing of the incident angle.

Smith and Gidlow (1987) approximation: they used Gardner's relation to eliminate the density term from Aki and Richards approximation and introduced:

$$R \approx VR_P\, \Delta v_P/v_P + VR_S\, \Delta v_S/v_S, \quad (2)$$

where,

$VR_P = 5/8 - 1/2(\gamma\sin^2\theta) + ½(\tan^2\theta)$, $VR_S = -4\gamma\sin^2\theta$, $\gamma = v_S/v_P$.

VR_P and VR_S are functions only of the v_P and the v_S/v_P models. This weighted stacking scheme was called geo-stack.

Fatti et al., (1994) approximation: they rewrote the geo-stack equation in terms of compressional and shear impedances in case the Gardner's relationship did not hold (making a limited angle assumption in which the third term was dropped):

$$R \approx ½(1 + \tan^2\theta)\Delta I_P/I_P - 4(\gamma\sin^2\theta)\Delta I_S/I_S, \quad (3)$$

where I_P and I_S are the P- and S-impedances, respectively.

The presence of outliers in amplitudes of a normal move out (NMO) corrected gather would causes an error in the least-squares regression within the AVA inversion. In this case, the inversion is considered to be non-robust and to cope with, some robust norms base on an iteratively reweighted least square process (Myers, 1990, p. 351) have been introduced into the seismic inverse problems. In this study, the processes of the AVA inversion were based on the robust regression.

V_S/V_P DETERMINATION

One of the critical input parameters to the approximations of Smith and Gidlow (1987) and Fatti et al. (1994) is the ratio of v_S/v_P. In an unexplored region the impedance ratio is usually unknown or at least inaccurate. This causes a scaled estimation of corresponding AVA attributed which also cause erroneous hydrate/gas saturations. In current study a simulated annealing (SA) global optimization approach (Kirkpatrick et al., 1983) was taken to overcome the problem of uncertain impedance ratio. The acceptance criterion for a realization is minimization of the difference between the observed AVA characteristics and the forward modeled AVA response.

HYDRATE/GAS SATURATIONS

The AVA attributes were used to estimate BSR-vicinity hydrate and gas saturations via a set of (hydrates related) rock physics derived AVA attributes (RPDA). To achieve this, the AVA attributes were calculated for some pre-assumed hydrate and gas saturations values using effective medium theory (EMT) of Helgeraud et al. (1999). Then these calculated AVA attributes were compared with their corresponding field data AVA inverted attributes. The best match of field data attributes with models would suggest the hydrate and gas saturations in vicinity of the BSR. This made a straightforward approach to estimate the hydrate/gas saturations, considering different lithology, porosity and hydrate/gas distribution types.

AVA INVERSION RESULTS

To measure the error of estimation for each attribute, the AVA inversion was applied on 30 synthetic gather. This measurement made a criterion for selection of the appropriate attributes. Generation of a synthetic seismogram's package was based on considering a series of plausible hydrate/gas saturations. The EMT rock physics model was used for the elastic property calculation. The synthetic common mid-point (CMP) gathers were then generated based on these elastic properties while the wave-equation-based approach of Kennett (1985) was used as a forward algorithm. These gathers then inverted using equations (1) to (3). The actual and inverted attributes were quantitatively compared. For this comparison, two goodness-of-fit statistics were measured for each estimated attribute. These statistics were root mean square error (RMSE) and R-square. Table 2 shows the GOF for each attributes.

Figure 1 shows an East-West oriented seismic section in the Iranian sector of the Makran Accretionary Prism. No well has been drilled within the area and 2D seismic lines comprise all available dataset. AVA attributes were computed and analyzed for this section to characterize

Table 2. Goodness-of-fit statistics for the computed AVA attributes of synthetic modeling.

Reflectivity equation	AVA attribute	RMSE	NRMSE	R-square
Shuey approximation (1985)	Intercept	0.036	0.096	0.87
	Gradient	0.043	0.093	0.85
Smith and Gidlow approximation (1987)	VR_P	0.014	0.039	0.97
	VR_S	0.032	0.118	0.86
Fatti et al. approximation (1994)	I_P	0.039	0.104	0.81
	I_S	0.017	0.0643	0.96

hydrate bearing sediments and to estimate the hydrate/gas saturations. Amplitude recovery process was included: geometrical spreading compensation, attenuation compensation, array directivity correction, equalization and trim statics, amplitude to reflection conversion. Corresponding AVA attributes of equation (1) to equation (3) for BSR at every five common reflection points (CRP) are plotted in Figures 2 to 4, respectively. Figure 2a is the seafloor two way travel time. Except for some anomalous values at some CRP locations, curve of intercept

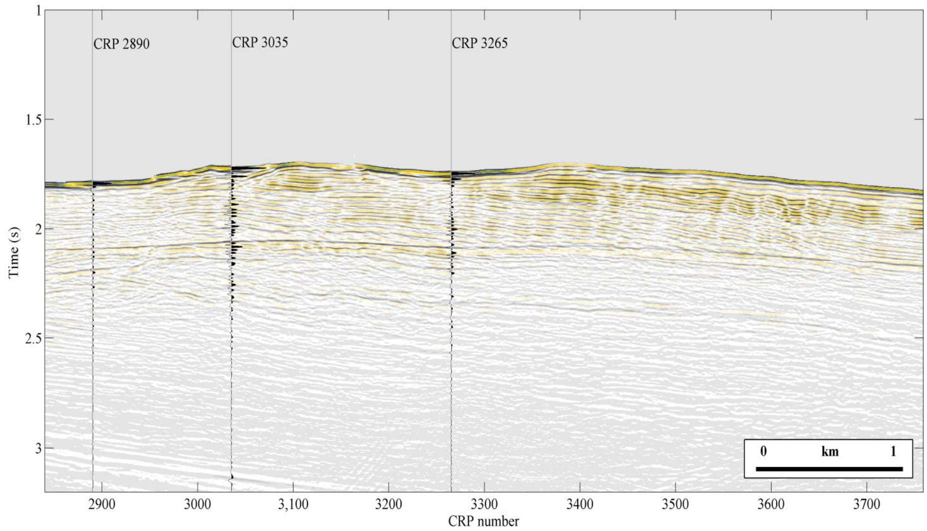

Figure 1. East-West oriented seismic stacked section in the Makran Accretionary Prism. Angle gathers of the indicated wiggle traces were used for quantification which are shown in Figure 5.

has gradually increasing trend (of magnitude) beneath local highs. The anomalous feature of intercept and gradient mostly can be attributed to the interfering of reflected events. v_S/v_P values in Figure 3a were determined from SA optimization at 9 CRPs (black asterisks) and linearly interpolated for intermediate CRPs. Blue symbols in 3b and 3c are the VR_P and VR_S attributes, respectively. In a similar way, the I_P and I_S are depicted in 4b and 4c. There is a clear analogy between corresponding P- and S-wave related attributes on Figures 3 and 4. The higher I_P values were interpreted as the depletion of v_P due to higher gas saturation. It could also be related to the free gas movement toward the crest of highs. The anomalous zones (A to C) were related to the interfering effects, so were flagged as erroneous and excluded from further analysis. Therefore, to prevent the interfering-induced errors in the quantification assessment, it was recommended that the estimation of saturations be limited to intervals with a steady AVA characteristic.

Figure 5 shows the three nominated CRPs from locations with low, intermediate and high stacked amplitudes, respectively. These CRPs were picked from intervals with minimum lateral variation of the I_P values. At each CRP, the AVA attributes were compared to the RPDAs to find the nearest corresponding hydrate/gas saturations. The BSR-vicinity hydrate saturations at CRP 2890, 3265 and 3035 were predicted 11%, 14% and 15% and gas saturations were predicted <1%, 2% and 3%, respectively. Blue line in 3 panels of Figure 5 is the inversion-derived linear approximation whereas red line is the linear approximations were calculated from RPDAs. The good match between two fitted lines indicated that estimated saturations completely define the actual AVA characteristic if the assumed input parameters were approximately correct.

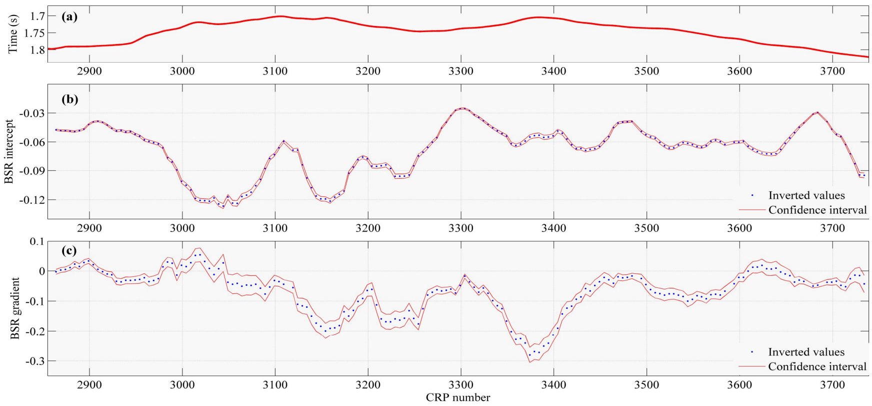

Figure 2. (a) Two way travel-time of sea floor reflector. (b) and (c) are AVA attributes of intercept and gradient, respectively. Blue circles are inverted values and the red lines indicate the confidence interval.

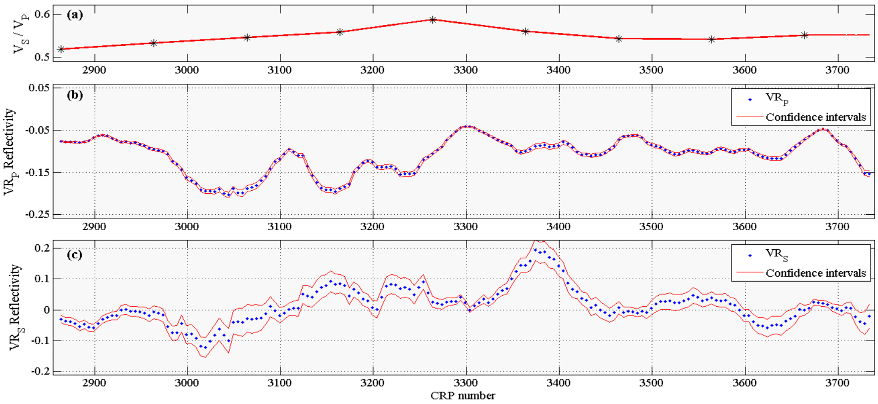

Figure 3. (a) Computed v_S/v_P values using (SA) optimization for nine CRPs (black asterisks) and interpolated for other intermediate CRPs. (b) and (c) are AVA attributes of VR_P and VR_S, respectively. Blue circles are inverted values of every five CRPs and the red lines indicate the confidence interval.

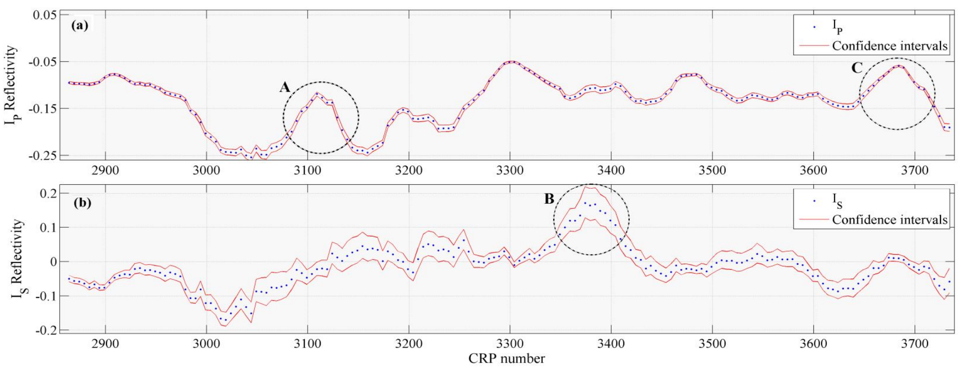

Figure 4. (a) and (b) are AVA attributes of I_P and I_S, respectively computed for the BSR. Circles A to C mark the zones where the interfering caused the anomalous AVA attribute values.

CONCLUSIONS

The results of an AVA inversion for synthetic models showed that inaccuracy in density/velocity relation and v_S/v_P resulted in a deviation of estimated attributes from a perfect correlation. However, the intercept/gradient and I_P/I_S were preferred due to lower error of estimation and because no density/velocity assumption is required for their derivation.

Applying the SA optimization to derive v_S/v_P compensated for the lack of knowledge on S-wave characteristics and provided more accurate calculation of AVA attributes. Using EMT rock physics models and I_P/I_S attributes, the hydrate saturations in vicinity of the BSR were predicted to be 11%, 14% and 15% for nominated locations with low, intermediate and high stacked amplitudes, respectively. The gas saturations for these locations were < 1%, 2% and 3%, respectively. This approach provided a straightforward seismic quantification method for the assessment of inferred and indicated hydrate resources.

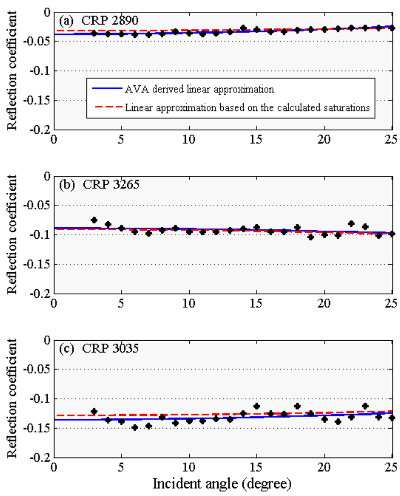

Figure 5. Linear approximations of reflection coefficient variations for three representative CRPs. In each part, the solid blue line is the linear approximation of reflectivity and derived from an AVA inversion with a robust linear LSR. Attributes of this fitting (here the I_P and I_S) are then compared to their RPDA equivalents to find the nearest values. The dashed red line is the linear approximation which is calculated with these nearest RPDA equivalents. (a), (b) and (c) are the CRPs with low, intermediate and high post-stack BSR amplitudes, respectively. The locations of CRP are indicated in Figure 1.

REFERENCES

Aki, K., Richards, P.G., 1980, Quantitative seismology, theory and methods: W. H. Freeman and Company.

Andreassen, K., Hart, P.E., and MacKay, M., 1997, Amplitude versus offset modeling of the bottom simulating reflection associated with submarine hydrates: Marine Geology, **137**, 25–40.

Fatti, J. L., Vail, P.J., Smith, G.C., Strauss, P.J., and Levitt, P.R., 1994, Detection of gas in sandstone reservoirs using AVO analysis: A 3-D seismic case history using the geostack technique: Geophysics, **59** 1362–1376.

Helgerud, M.B, Dvorkin, J., Nur, A., Sakai, A., and Collett, T.S., 1999, Elastic wave velocity in marine sediments with gas hydrates: effective medium modeling: Geophysical Research Letters, **26**, 2021–2024.

Kennett, B., 1985, Seismic wave propagation in stratified media: Cambridge University Press.

Kirkpatrick, S., Gelatt, C.D., and Vecchi, M.P., 1983, Optimization by simulated annealing: Science, **220**, 613–680.

Myers, R.H., 1990, Classical and Modern Regression with Applications: Duxbury, Boston.

Milkov, A.V., and Sassen, R., 2002, Economic geology of offshore gas hydrate accumulations and provinces: Marine and Petroleum Geology, **19**, 1-11.

Shuey, R.T., 1985, A simplification of the Zoeppritz equations: Geophysics, **50**, 609-614.

Smith, G.C., and Gidlow, P. M., 1987, Weighted stacking for rock property estimation and detection of gas: Geophysical Prospecting, **35**, 993–1014.