AVO ANALYSIS IN GAS HYDRATE EXPLORATION AND THE POSSIBILITY OF ITS APPLICATION IN DEEP WATER CONTINENTAL SHELF OF VIETNAM

Nguyen Thu Huyen, Nguyen Trung Hieu, Tong Duy Cuong, Nguyen Manh Hung, Nguyen Danh Lam, Trinh Xuan Cuong
Vietnam Petroleum Institute
Email: huyennt@vpi.pvn.vn

Summary

AVO, which stands for Amplitude Variation with Offset - or more simply, Amplitude Versus Offset, is a seismic technique that looks for direct hydrocarbon indicators using amplitudes of prestack seismic data. The AVO technique became very popular in the petroleum industry, as one could physically explain the seismic amplitudes in terms of rock properties. For example, bright-spot anomalies (i.e. the high amplitude reflections seen on the P-wave stacked section) could be investigated before stack to see if they also had AVO anomalies. It can help us distinguish the geological objects that created bright-spot anomalies, such as gas-bearing sandstones, coal seams or volcanoes.

AVO analysis proved successful in certain areas of the world for gas hydrate exploration. In this paper we describe AVO analysis methods and some examples of using AVO in gas hydrate exploration in the world as well as the possibility to apply it in deep water areas on the continental shelf of Vietnam.

Key words: *Gas hydrate, AVO, BSR, anomaly amplitude, deep water area*

1. Introduction

Gas hydrate was considered by scientists as a curiosity and by the petroleum industry as a nuisance until its very recent recognition in the natural environment. Within more than thirty years of its first discovery, however, both industry and governments had begun to explore the potential of hydrate as an energy [10, 11]. Recent interest in gas hydrate has grown not only in the U.S but also in some European Union countries, Japan, South Korea, China and Taiwan. The primary interest is the potential of gas hydrate to supply large quantities of methane to commercial energy markets in this century and beyond.

Gas hydrate is found in the ocean because of a coincidence of rising pressure and diminishing temperature with increasing water depth (Figure 2), where there are huge quantities seismic data but very sparse well data. One of the primary issues for gas hydrate research is the interpretation of seismic data to determine the possible existence of gas hydrate.

Gas hydrate can be detected from seismic data by observations of Bottom-Simulating Reflectors (BSR). A BSR is parallel to the seafloor reflector with opposite polarity (Figure 3 and 4). A bottom-simulating reflector (BSR) is clearly observed on the seismic section with a reversed polarity compared to that of the seabed reflection. Instantaneous amplitude section clearly shows lateral variations of the BSR. The zero-phase waveform of the BSR is distinct and weak reflectors above the BSR can be observed on the instantaneous phase section. AVO analysis shows the absolute values of the negative BSR amplitude increasing with offset. AVO analysis could also be useful in differentiating amplitude anomalies related to gas hydrate and those resulted from anomalous lithologies, because the amplitude anomalies induced by anomalous lithologies can be typically observed on both P- and S-wave sections. Unfortunately, S-wave is commonly not recorded. One solution to this problem is to use AVO method on conventional P-wave data, which allows us to derive S-wave data without actual recording (Figure 1).

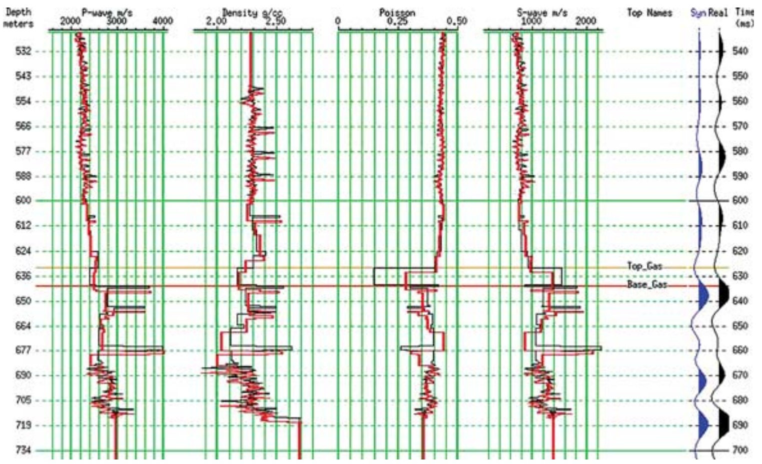

Figure 1. *Quantitative AVO analysis to estimate P- and S-wave velocities and density. The black curves are before inversion while the red curves show the same logs after inversion. Synthetic seismic trace (blue) shows very good fit with real seismic data*

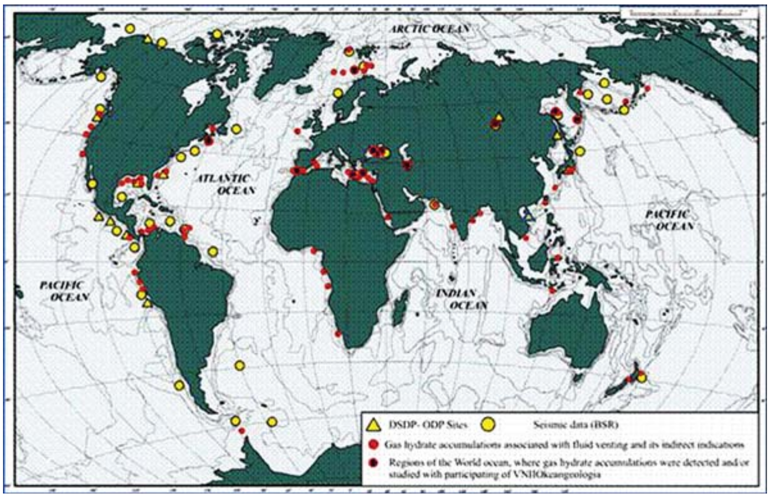

Figure 2. *Map showing regions where gas hydrate accumulations were detected and studied [9]*

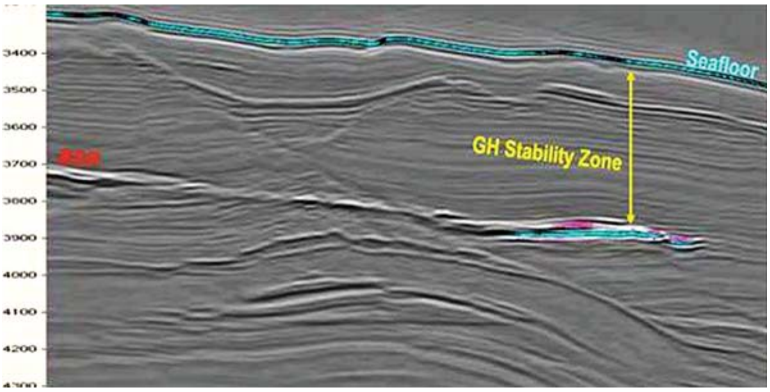

Figure 3. *Seismic section in the deep water area of the Gulf of Mexico: BSR is a strong reflector and parallel to the seafloor [13]*

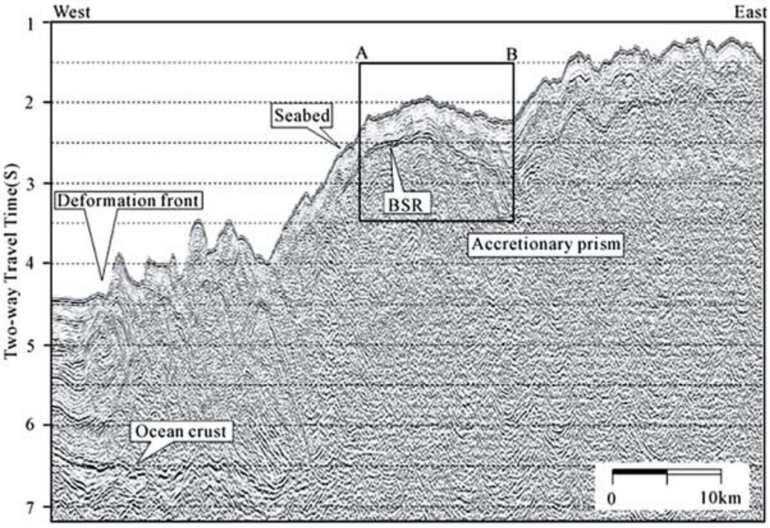

Figure 4. *Seismic section in the deep water area of Taiwan BSR - is a strong reflector and parallel to the seafloor [14]*

AVO analysis was first mentioned in 1984 when Ostrander published a break-through paper in "Geophysics" [1]. He showed that the presence of gas in a sandstone layer capped by a shale layer would cause an amplitude variation with offset in prestack seismic data. He also found that this change was related to the reduced Poisson's ratio caused by the presence of gas. One year later, Shuey [2] confirmed mathematically via approximations of the Zoeppritz equations that Poisson's ratio was the elastic constant most directly related to the offset-dependent reflectivity for incident angles up to 30°.

AVO analysis is carried out after the raw seismic data have been processed using an amplitude-preserved processing sequence. In this paper we describe the AVO technique and some examples of using AVO in gas hydrate exploration in the deep water in the Gulf of Mexico and in Taiwan [13, 14] as well as the possibility to apply it in deep water areas on the continental shelf of Vietnam.

2. AVO intercept and gradient analysis

Analysis of AVO or amplitude variation with offset seeks to extract rock parameters by analysing seismic amplitude as a function of offset. The reflection coefficient for plane elastic waves as a function of reflection angle at a single interface is described by the complicated Zoeppritz equations [3]. For analysis of P-wave reflections, a well-known approximation is given by Shuey [2]. He linearly approximated the Aki-Richards equation and kept only the second-order term:

$$R(\theta) = R_P + G\sin^2\theta \qquad (1)$$

where: R(θ) is the reflection coefficient with incident angle θ

$R_P = \frac{1}{2}\left[\frac{\Delta V_P}{V_P} + \frac{\Delta\rho}{\rho}\right]$ is the P-wave reflection coefficient of normal incidence (θ = 90°)

$G = \frac{1}{2}\frac{\Delta V_P}{V_P} - 2\frac{V_S^2}{V_P^2}\left[\frac{\Delta\rho}{\rho} + 2\frac{\Delta V_S}{V_S}\right]$ describes the variation at intermediate offsets

Equation (1) is linear if we could plot R(θ) as a function of $\sin^2\theta$. We could then perform a linear regression analysis on the seismic amplitude to come up with estimates of both intercept R_P and gradient G. When we perform this analysis at every sample on every gather, we create two sections, or volumes. The intercept section is similar to the conventional stack - except that it represents a better estimate of the vertical P-wave reflections (normal incident

P-wave reflections). The gradient contains information about both the P and S-wave reflections.

Assume that $V_P/V_S = 2$ then the formula for gradient G becomes:

$$G = R_P - 2R_S \qquad (2)$$

where: $R_S = \frac{1}{2}\left[\frac{\Delta V_S}{V_S} + \frac{\Delta \rho}{\rho}\right]$ is the S-wave reflection coefficient of normal incident ($\theta = 90^o$).

Equation (2) can be rewritten as: $R_S = (R_P - G)/2$. From this formula, it is obvious that the difference between intercept and gradient, after scaling, is the approximate S-wave reflectivity. If the intercept (P-wave) section shows a strong "bright spot", whereas the pseudo-S-wave (intercept minus gradient) section does not show a "bright spot," it might indicate the presence of BSR.

Equation (1) was further approximated by Verm and Hilterman [4] to:

$$R\ (\theta) = R_P \cos^2\theta + RS \sin^2\theta \qquad (3)$$

where: $PR = \left[\frac{\Delta\sigma}{\left(1-\sigma_{avg}\right)^2}\right]$ is the Poisson's reflectivity;

$\Delta\sigma$ is the change in Poisson's ratio;

σ_{avg} is the average Poisson's ratio.

Assuming that $\sigma_{avg} = 1/3$ we have $PR = {}^9\!/_4\,\Delta\sigma$ and equation (3) becomes:

$$R(\theta) = R_P + \left(\frac{9}{4}\Delta\sigma - R_P\right)\sin^2\theta \qquad (4)$$

Comparing equations (1) and (4) we have: $G = {}^9\!/_4\,\Delta\sigma - R_P$ or:

$$\Delta\sigma = \left(R_P + G\right) \times {}^4\!/_9 \qquad (5)$$

Equation (5) shows that the sum of the intercept and the gradient can be shown to represent the approximate Poisson's ratio change, where the Poisson's ratio is related to the square of the P-wave to S-wave velocity ratio $\left(\frac{V_P}{V_S}\right)^2$. Thus, a negative Poisson's ratio change is associated with the top of a gas zone, whereas a positive change is associated with the base.

Furthermore, the product of AVO intercept and gradient (R_P x G) is a very helpful parameter in areas where we expect soft sands with hydrocarbons, which is AVO class III. Soft sand with hydrocarbons will have strong negative intercept and a strong negative gradient. The product will be a strong positive. Non-hydrocarbon reflectors will be weak or have negative products. Thus, the product parameter is a nice attribute to distinguish BSR-related bright spots from "false" bright spots.

With the AVO analysis results from line AB in Figure 4 (deep water of Taiwan) [14], the BSR is negative in the R profile (Figure 5a), indicating that the impedance below the BSR is smaller than that above the BSR. The G-attribute values along BSR in section AB are also negative (Figure 5a), implying that the absolute value of the BSRs amplitude increases with incident angles. The AVO anomaly (Figures

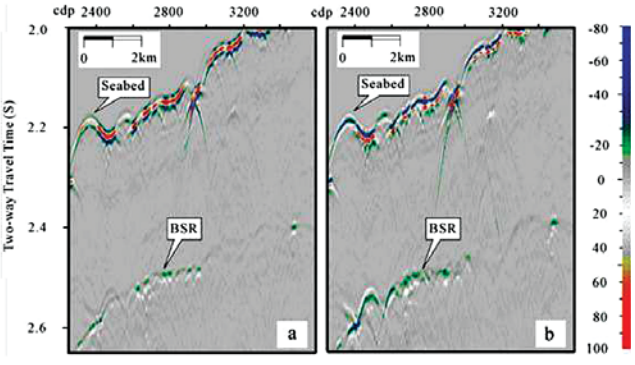

Figure 5. R (a) và G (b) section [14]

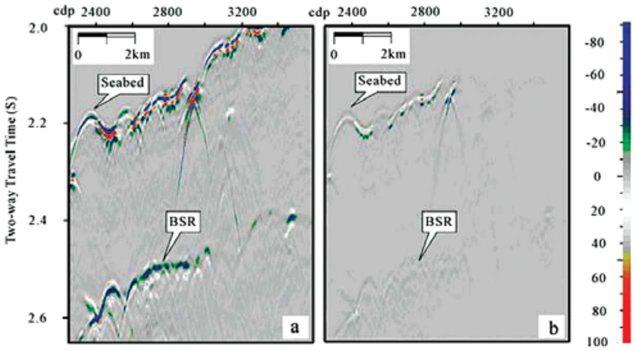

Figure 6. R + G (a) và R - G (b) section [14]

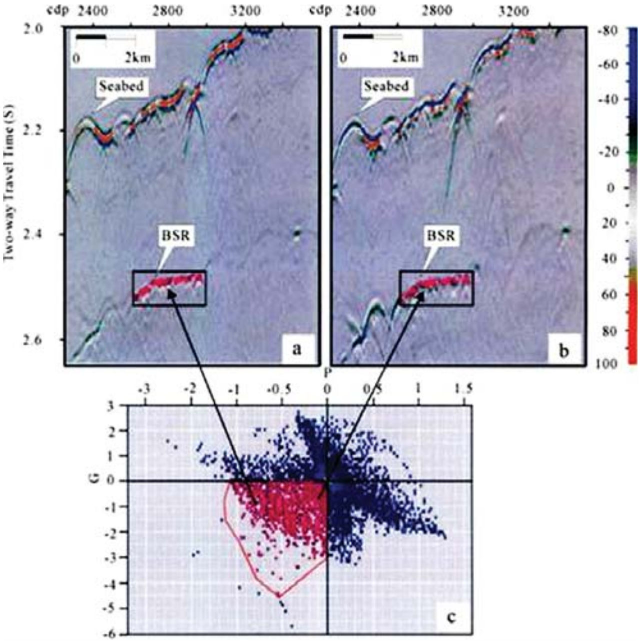

Figure 7. R section (a); G (b); R vs G crossplot (c)[14]

7a, b) of the BSR belongs to type III [5] and the BSR's value lies in the third quadrant of the crossplot of the R and the G sections [6] (Figure 7c), thus the sediments should contain a hydrate layer above the BSR and free gas below the BSR.

3. AVO analysis using seismic amplitude

Mathematical expressions of AVO are, in fact, usually presented in terms of *relative* amplitude, i.e., reflection coefficient, or reflection amplitude normalised with respect to incident-wave amplitude. In practice, however, AVO analysis is carried out using seismic amplitudes (*absolute* amplitude). This leads us to a very important question: how can we obtain such relative amplitudes if we only observe seismic-trace amplitudes?

For example, Smith & Gidlow [8] write:

$$R_{PP}(\theta_i) = A_i \frac{\Delta\alpha}{\alpha} + B_i \frac{\Delta\beta}{\beta} \qquad (6)$$

where: $\alpha = V_P$ and $\beta = V_s$

$$A_i = \frac{5}{8} - \frac{1}{2}\frac{\beta^2}{\alpha^2}\sin^2\theta_i + \frac{1}{2}\tan^2\theta_i \text{ and } B_i = -4\frac{\beta^2}{\alpha^2}\sin^2\theta_i \qquad (7)$$

Both of these expressions, (8) and (9), are clearly dimensionless; they involve relative amplitudes. However, Smith & Gidlow go on to say "if the actual amplitude of each offset sample is a_i, then the mean square error… is given by":

$$\varepsilon = \sum_{i=1}^{n}\left(A_i\frac{\Delta\alpha}{\alpha} + B_i\frac{\Delta\beta}{\beta} - a_i\right)^2 \qquad (8)$$

Further, they give results of their least-squares regression analysis for α and β reflectivities in the form:

$$\frac{\Delta V}{V} = \sum_{i=1}^{n} a_i C_i \qquad (9)$$

where V stands for α or β. C_i are weights that are clearly dimensionless, as they involve only sums and products of dimensionless A_i's and B_i's. Thus the a_i values must clearly also be dimensionless, or normalised with respect to incident-wave amplitude.

The actual trace-sample values could be written as Ka_i, where K is a scaling constant that we assume initially to be unknown. Then (11) becomes:

$$K\frac{\Delta V}{V} = \sum_{i=1}^{n}(Ka_i)C_i \qquad (10)$$

in which Ka_i are trace-sample values. And (8) becomes:

$$KR_{PP}(\theta_i) = A_i\left[K\frac{\Delta\alpha}{\alpha}\right] + B_i\left[K\frac{\Delta\beta}{\beta}\right] \qquad (11)$$

in which the bracketed quantities are known from the regression analysis.

Equation (13) shows that, in order to obtain relative amplitudes from seismic amplitudes we need to estimate the value of *K*. If we do not estimate this value and calibrate the seismic data prior to AVO analysis then we can only perform the qualitative AVO analysis but not quantitative analysis. AVO inversion of the seismic data without scaling them to the level of reflection coefficients will give incorrect elastic parameters such as P-wave and S-wave velocities and density.

Estimation of the value of *K* requires forward modeling to create multi-offset synthetic seismogram from dipole sonic information. For each offset trace the root-mean-square (RMS) amplitude is calculated and then matched to the corresponding seismic data.

In order to study the characters of gas hydrate in the deep area of the Gulf of Mexico [13] (Figure 3), qualitative AVO analysis can be performed directly using seismic amplitudes. To obtain relative amplitudes from seismic amplitudes, seismic data (Figure 9) is scaled, prior to AVO, from seismic velocity and density (Figure 8), then the AVO

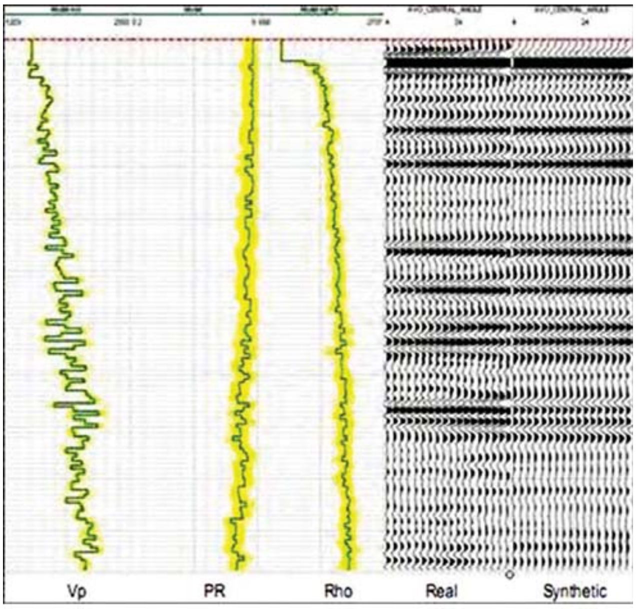

Figure 8. Synthetic seimogram established from data in the deep water of Gulf of Mexico [13]

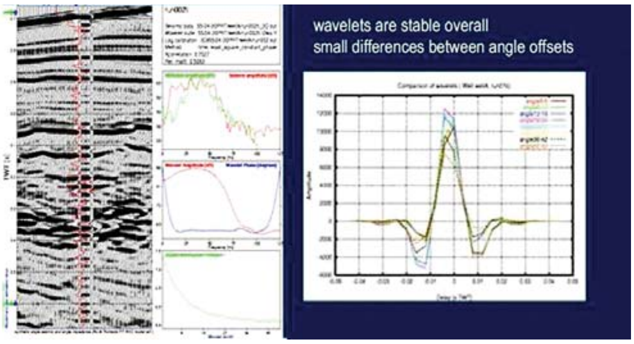

Figure 9. Amplitude correction with reflection coefficients [13]

is performed. As per integrated analyses above, the gas hydrate layer above the BSR and the free gas layer below the BSR may most probably occur in the place where strong BSRs are observed as a base of gas hydrate stability (Figure 10).

4. The possibility to apply AVO in deep water areas on the continental shelf of Vietnam

Beside the traditional petroleum resources that have an important role in the industrialisation and modernisation of the country, gas hydrate that may exist in deep water areas on the continental shelf of Vietnam can be another source of fossil fuels in the future.

Oil and gas exploration in Vietnam began in the 60s of the last century, but the research and investigation of gas hydrate potential has been a "Topical Question". Since 2006, Petrovietnam and the Ministry of Natural Resources and Environment have organised several conferences and seminars on the issue of gas hydrates, and proposed to the Government "an integrated research programme on gas hydrate potential in the continental shelf of Vietnam". On 24 September 2007, the Prime Minister issued Decision No. 1270/QD-TTg to add "The basic research and investigation programme of gas hydrate potential in Vietnam's territorial waters and continental shelf" programme to the tasks of the Master Plan for "Basic survey and integrated management of marine resources until 2010 and vision to 2020".

Several companies in Vietnam have conducted research, investigation and evaluation of gas hydrate potential in Vietnam and initially made statements about the presence of gas hydrate in the deep water areas on the continental shelf of Vietnam (from 500m of water) [15, 16].

On the basis of seismic data covering the Vietnam continental shelf and neighbouring areas (Figure 11) and under the direction of Petrovietnam, the Vietnam Petroleum Institute is currently carrying out a State Project to collect, analyse and integrate data to identify the indicators of gas hydrate in Vietnam's continental shelf".

Based on the seismic data analysis as well as integrated analysis, the results of the research conducted by the Vietnam Petroleum Institute allow the prediction of gas hydrate presence in the deep-water areas on the continental shelf of Vietnam. On some seismic sections in the study area (Figure 12), the presence of strong reflective surfaces that lie continuously parallel to the sea floor (BSR) within the blank zones, gas chimneys, and amplitude anomalies can be related to gas hydrate.

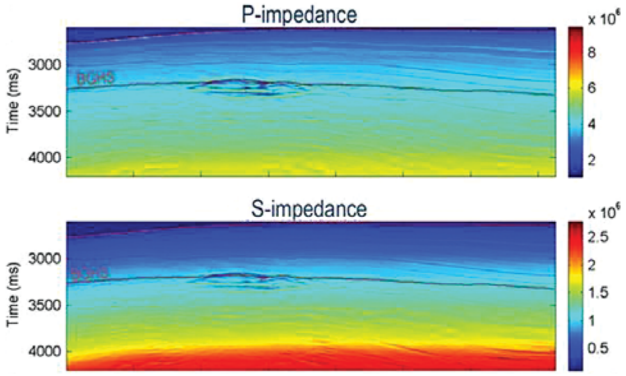

Figure 10. *AVO result for studying the gas hydrate in the deep area of the Gulf of Mexico [13]*

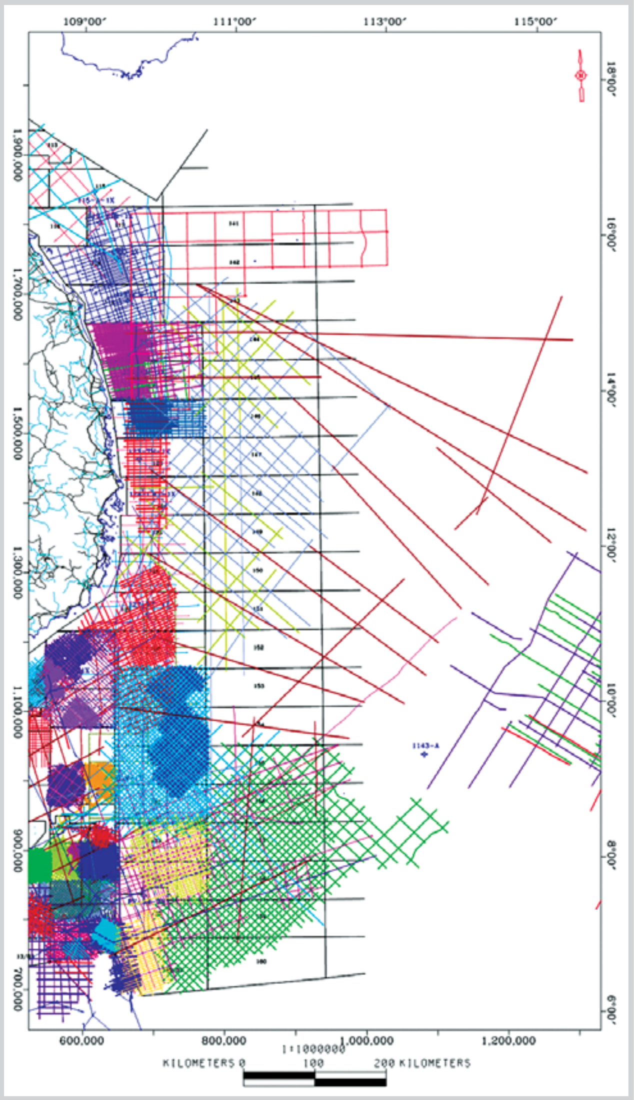

Figure 11. *Location map showing seismic lines used in the gas hydrate project*

From the seismic data with the gas hydrate indication as presented and in combination with related geological data, special analysis of seismic attributes, especially

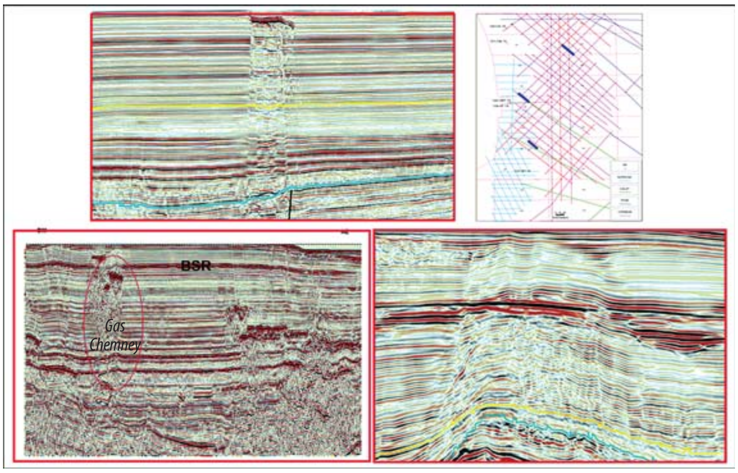

Figure 12. The BSR, gas chimney, and amplitude anomalies can be related to gas hydrate in deep water areas on the continental shelf of Vietnam

AVO analysis, can be conducted to predict the existence of BSR to explore gas hydrate in the deep water areas on the continental shelf of Vietnam.

5. Conclusion

In this paper we presented an overview of AVO analysis method and the results of applying AVO analysis in gas hydrate research. AVO analysis results indicate that the absolute value of the BSR amplitude increases with offset. The gas hydrate layer above the BSR and the free gas layer below the BSR may probably occur in the place where strong BSRs are observed as a base of gas hydrate stability (BGHS).

Based on the results of the State Project carried out by the Vietnam Petroleum Institute to collect, analyse and integrate data to identify the indicators of gas hydrate in the Vietnam continental shelf, it can be concluded that the AVO analysis can be conducted to predict the distribution of BSRs to explore gas hydrate in deep waters of the continental shelf of Vietnam.

References

1. W.J.Ostrander. *Plane-wave reflection coefficients for gas sands at non-normal angles of incidence.* Geophysics. 1984; 49(10): p. 1637 - 1648.

2. R.T.Shuey. *A simplification of the Zoeppritz equations.* Geophysics. 1985; 50(4): p. 609 - 614.

3. K.Aki, P.G.Richards. *Quantitative seismology: Theory and methods*. Freeman. 1980.

4. Richard Verm, Fred Hilterman. *Lithology color-coded seismic sections: The calibration of AVO crossplotting to rock properties*. The Leading Edge. 1995; 14(8): p. 847 - 853.

5. Steven R.Rutherford, Robert H.Williams. *Amplitude-versus-offset variations in gas sands*. Geophysics. 1989; 54(6): p. 680 - 688.

6. John P.Castagna, Steven W.Smith. *Comparison of AVO indicators: A modeling study*. Geophysics. 1994; 59(12): p. 1849 - 1855.

7. John P.Castagna, Herbert W.Swan. *Principles of AVO crossplotting.* The Leading Edge. 1997; 16: p. 337 - 342.

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

9. Michael D.Max. *Natural gas hydrate in oceanic and permafrost environments.* Kluwer Academic Publishers. 2003.

10. Takashi Uchida. *Methane hydrate: A future energy resource?* Technology Research Center, Japan Oil, Gas and Metals National Corporation. 2004.

11. Michael D.Max, Arthur H.Johnson, William P.Dillon. *Economic geology of natural gas hydrate*. Springer. 2006.

12. P.Wang et al. *Initial reports*. 2000.

13. Dianna Shelander, Jianchun Dai, George Bunge, Dan McConnel, Niranjan Banik. *Predicting gas hydrates using prestack seismic data in deepwater Gulf of Mexico*. AAPG Geoscience Technology Workshop, Houston, Texas. 16 March, 2010.

14. Hui Deng, Pin Yan, Hailing Liu, Wenzao Luo. *Seismic data processing and the characterization of gas hydrate bearing zone offshore of Southwestern Taiwan.* Terrestrial Atmospheric and Oceanic Sciences. 2006; 17(4): p. 781 - 797.

15. Vietgazprom. *Seismic data processing and interpretation of Block 129-132 offshore Vietnam*. 2010.

16. Vietgazprom. *Complex marine geology-geophysical exploration of gas hydrate accumulations offshore Vietnam*. 2011.

17. Prime Minister. *The basic research and investigation programme of gas hydrate potential in Vietnam's territorial waters and continental shelf*. Decision No. 1270/QD-TTg.