



Impact of Phase Variations on Quantitative AVO Analysis

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Summary

Effectiveness of AVO techniques has always been a concern for practicing geoscientists in accessing and modelling reservoirs due to wavelet instability in seismic data. In spite of best efforts made during processing, most often, end product is mixed phase seismic data. This paper is an attempt to study the effect of phase in pre-stack seismic data for quantitative AVO analysis to characterise reservoirs for detection, delineation and development. AVO attributes corresponding to known gaseous reservoirs, computed from zero phase seismic show better AVO anomalies. Prior to AVO analysis, to understand AVO classification, petrophysical analysis was carried out for establishing the relation between elastic parameters and also with seismic signatures. AVO modelling has been used to demonstrate the superiority of zero phase seismic data at known gaseous reservoir sands. In absence of source signature, application of well log data for estimation of wavelet present in seismic was made and by dephasing, the mixed phase data was converted to optimum zero phase. In wildcat exploratory areas, explorationists try to establish AVO anomaly using available mixed phase seismic data. It is found that, at times, AVO attributes are not well defined to differentiate AVO anomalies with reference to background trend extracted from this mixed phase data set. In absence of well data, phase rotation of pre-stack gathers at fixed intervals and their analysis is the best possible solution. This has been discussed in detail by applying on a data set at pre-drill stage and confirming the AVO anomaly which has been proved by subsequent drilling. It is also demonstrated that phase rotation is a robust technique and does not generate spurious AVO response, by applying it at known dry well. This approach of analysing well, synthetic and seismic data together for AVO analysis has increased the level of confidence of interpreters for E & P activities related to the gaseous reservoirs.

Introduction

With the advancement of computing and interpretation technology the pre-stack seismic data interpretation has gained popularity among geoscientists. Recent advances in amplitude variation with offset (AVO) technology have demonstrated that the measurement of conversion of compressional energy to shear energy at interfaces can yield significant information about the fluids and lithology present. Many theoretical, numerical and real data studies carried out during last three decades have witnessed the success of AVO technique (Castagna et al., 1998, Pramanik et al., 2000, Cambois, 2000, Goodway, 2001, Roden et al., 2005). The primary attributes extracted from AVO analysis are the intercepts and the gradients which are obtained from NMO corrected pre-stack amplitudes of conventional P-wave seismic data. These attributes have proven to be a useful seismic lithology tool and direct hydrocarbon indicator in the hunt of oil and gas. However, at times, it has been observed that these AVO attributes do not give clear-cut information in terms of lithology, fluid and other reservoir properties due to signal distortions introduced during acquisition and processing stages. In signal distortion, the amplitude, frequency and phase of seismic data gets altered and pose a major challenge to the interpreters in reservoir

characterization (Roden and Sepulveda, 1999, Singh and Srivastava, 2004, Roden et al., 2005).

Phase is one of the critical seismic attributes which needs fundamental understanding and special attention by the interpreters. The estimation of phase component of the seismic wavelet is one of the most difficult problems faced in the seismic data processing even today. In spite of best efforts made during data processing, it is nearly impossible to obtain a zero phase wavelet and as a result the wavelet of processed data remains in mixed phase which varies with time, space and offset. Optimum Zero phase seismic data is always desired for quantitative reservoir characterization.

In this work, the impact of phase variations in pre-stack seismic data for quantitative AVO analysis has been demonstrated. AVO attributes generated from phase synthetic NMO corrected gathers and their cross-plot analysis show that reduction of phase variability in NMO corrected CDP gathers prior to AVO analysis has added significant value to AVO interpretation for prospecting of gaseous reservoirs.

Theoretical background of AVO analysis

The reflection coefficient equation which determine the variation of reflection amplitude of P-wave with offset

and six elastic parameters of the two layers [compressional velocities V_{p1} and V_{p2} (average is V_p); shear velocities V_{s1} and V_{s2} (average is V_s); the densities r_1 and r_2 (average is r)] was originally derived by Zoeppritz in 1919 from the continuity of displacement and stress in both the normal and tangential directions across an interface. This equation provides a means to derive exact amplitude of reflected P-waves but was unable to give an intuitive understanding of how the recorded amplitudes relate to the varying physical parameters. Over the years, a number of approximations to the Zoeppritz equation have been made. In 1985, Shuey rearranged P-wave reflection coefficient equation in such a way that the influence of offset angle is separated. Shuey’s (1985) equation is written as

$$R(\theta) = (P/2)[(\Delta V_p/V_p) + (\Delta\rho/\rho)] + [\Delta\sigma/(1-\sigma^2)] \sin^2 \theta + (1/2)[(\Delta V_p/V_p)(\tan^2 \theta + Q)] \quad (1)$$

where

$$P = (1/2) - [\{ 2 (V_s/V_p)^2 \} \sin^2 q]$$

$$Q = - (2V_s/V_p)^2 \sin^2 \theta$$

$$V_p = (V_{p1} + V_{p2})/2$$

$$V_s = (V_{s1} + V_{s2})/2$$

$$\rho = (\rho_1 + \rho_2)/2$$

$$\Delta\rho = (\rho_2 - \rho_1)$$

$$\Delta V_p = (V_{p2} - V_{p1})$$

$$\Delta V_s = (V_{s2} - V_{s1}) \text{ and}$$

$$\theta = (\theta_i + \theta_r)/2, \theta_i = \text{angle of incidence,}$$

$$\theta_r = \sin^{-1} [(V_{p2}/V_{p1}) \sin \theta_i]$$

In equation (1) σ is known as Poisson’s ratio and is defined as $\sigma = [(1/2)(V_p/V_s)^2 - 1] / [(V_p/V_s)^2 - 1]$ and $\Delta\sigma = (\sigma_2 - \sigma_1)$.

The first term of the above equation influences the near traces, the second term starts its influence in the mid range of incident angles (15-30 degrees) and the last term influences the large angles (30 plus degrees). Shuey also recognized that the third term can be ignored for most of the AVO analysis. The two term P-wave reflection coefficient equation in rearranged form is written as

$$R(\theta) = A + B \sin^2 \theta \quad (2)$$

where $A = [(1/2) \{ (\Delta V_p/V_p) + (\Delta\rho/\rho) \}] =$ P-wave reflection coefficient at normal incidence or intercept,

$B = (1/2) \{ \{ (DV_p/V_p) - (D\rho/\rho) - 2(DV_s/V_s) \} \} =$ Slope or Gradient and depends on (V_p/V_s) ratio.

Careful observation reveals that the equation (2) represents a simple straight line formula which provide A as intercept and B as slope (or gradient) at each sample if $R(q)$ is plotted against $\sin^2 q$. In deriving the above expression

of P-wave reflection coefficient given in equation (2), following assumptions were made:

1. The medium of seismic wave propagation is isotropic and homogeneous.
2. The values D_r , DV_p and DV_s are small compared to V_p , V_s and r .
3. Angle of incidence is less than critical angle.
4. Shear wave velocity is assumed half of the P-wave velocity i.e., $(V_p/V_s) = 2$.
5. For angle of incidence ranging 0 to 30 degree, the value of $\tan q$ and $\sin q$ will be approximately same therefore; the contribution of third term in P-wave reflection coefficient equation (1) becomes insignificant and hence ignored for all practical purposes.

In practice, the AVO intercept is a band limited measure of the normal incidence while the AVO gradient is a measure of amplitude variation with offset or incidence angle.

Methodology

To utilise AVO technique quantitatively for detailed reservoir characterization during exploitation and production at post-drill stage and for direct hydrocarbon detection in exploration of clastic reservoirs at pre-drill stage, a workflow has been developed. This consists of extensive petrophysical analysis to establish the relation between elastic properties, estimation and reduction of phase variation in real seismic gathers through various available approaches, AVO modelling, generation of AVO attributes from synthetic and real seismic gathers and their cross plot analysis.

Petrophysical analysis

Petrophysical analysis is the key to relate the various elastic parameters derived from edited well log data and helps to extract extra meaningful information from seismic data in terms of direct hydrocarbon indicators, indication of reservoir quality, reservoir changes over time and “hidden” stratigraphic trapping potential. Cross plotting is a fundamental process in petrophysical analysis used in the selected depth interval to:

- understand how the rock properties are related
- determine the resolution of rock properties in various lithologies in the area
- contribute velocity constraints such as mud rock line values to AVO analysis of seismic data
- determine the sensitivity of various attributes to fluid effects.
- estimate AVO attributes characterizing a given reservoir.



Estimation of phase variation and its reduction in real CDP gathers

The reflected energy from an interface is concentrated in peaks and troughs only in case of zero phase seismic data and it is found most suitable for reservoir characterization. In spite of best processing efforts, it is nearly impossible to achieve zero phasing due to various acquisition and processing assumptions, and presence of noise. These complications lead to mixed phase wavelet in amplitude preserved NMO corrected gathers. Several methods from preliminary to detailed interpretation are practiced for understanding the phase variations of wavelet. These are through visual inspection of phase response at distinctive reflecting interfaces, wavelet estimation, phase rotation and instantaneous seismic attributes.

An estimation of the wavelet character and associated phase can quite often be visually identified at distinctive reflecting interfaces. This includes the water bottom on marine data, the top and bottom of thick stratigraphic units, regional events and direct hydrocarbon indicators. But through visual inspection, it is difficult to distinguish out of phase response of less than 30-35deg.

The link between recorded seismic waveform, stratigraphy and rock properties is the seismic wavelet and its accuracy is of fundamental importance. A variety of methods are being used in practice for wavelet estimation and to understand the phase variations. Some of them are:

- ▶ Estimation of amplitude and phase spectra using deterministic measurements such as VSP and marine source signatures (Johnston et al., 1997).. But this method does not account source radiation pattern and also do not include the effects of stacking and migration.
- ▶ Estimation of amplitude and phase spectra using both seismic and well log measurements. Full wavelet and constant phase wavelet can be estimated by this semi-deterministic approach (Hampson and Gailbraith, 1981). In this method estimation of wavelet critically depends on the quality of the tie between well logs and seismic.
- ▶ Estimation of amplitude and phase spectra using seismic data alone. This is being done using statistical approach through autocorrelation or cross- spectral analysis or by maximum entropy spectral analysis (Lindsey, 1988, Brown et al., 1988). In this method, phase is assumed known from other source and it also assumed that the seismic response is the result of convolution of minimum

phase wavelet with random series of reflectivity. This assumption is often valid in reality.

The phase variation of extracted seismic wavelet and its tolerance limit is one of the most important aspects specially when striving for the maximum accuracy in seismic-to-well tie. For accurate reservoir characterization using advanced techniques like inversion and AVO, a phase error of less than 10 degree can be tolerated (White, 1997).

In the wildcat areas, the above mentioned methods of wavelet estimation can not be utilised effectively. Under these circumstances, seismic data can be rotated through a series of phase angles with reference to a distinctive reflection response close to the target of interest and analysed for estimation of maximum energy in a single peak or trough depending upon the polarity of the seismic data. The maximum energy case will be closer to zero phased seismic data. However, phase rotation method requires:

- the geology to produce a distinctive reflecting response
- good signal to noise data where reflective character is distinguishable
- awareness of variability of the acoustic response associated with different interfaces. These could be any thing from a gradational lithologic change to a sharp contact.

AVO Modeling, generation of AVO attributes and their Cross-plot analysis

The procedures for AVO modelling are straight forward. The requirement for successful implementation are a fundamental understanding of pore fluid and lithologic relationships with the seismic response, the identification and extraction of the appropriate AVO attributes from the models and their cross-plotting. The steps involved in modelling are:

- Editing and preparation of well logs
- Generation of NMO corrected synthetic gathers for minimum and zero phase wavelets using two term reflection coefficient equation given in eqn.(2).
- Generation of basic AVO attributes(the intercept (A), the gradient(B) and their combinations for minimum and zero phase NMO corrected gathers

- Understanding of AVO classification to relate appropriate AVO attributes with proper geologic setting (Rutherford and Williams, 1989, Castagna and Swan, 1998).
- Cross-plot generation in A-B plane and their analysis (Ross, 2000).

Results and discussions

In order to demonstrate the effectiveness of the methodology we have chosen real data examples from one of the Indian sedimentary basins where clastic reservoirs of Pliocene age are producing hydrocarbons in commercial quantity. For these Pliocene reservoirs, P-wave seismic amplitudes are generally considered as the most robust direct hydrocarbon indicators. Exploration prospects based on a sound geologic model and supported seismic amplitude anomalies are highly prospective. From this area, well A which is producing gas from first three upper objects and oil from the lower most object has been taken up for analysis. Sample logs with lithology of Well-A are shown in Fig.(1). The relationships between petrophysical parameters have been established by extensive cross-plotting (Figs.2a-2f). The gas charged sands are distinguishable from the background trend. These sands are low impedance having lower V_p and high V_s values and they exhibit class-2/3 type AVO anomalies (Rutherford and Williams, 1989, Castagna and Swan, 1998).

For forward AVO modelling, the edited logs were smoothed at every 2m interval. Using these logs, minimum and zero phase Ricker wavelets of 30Hz and two term reflection coefficient equation given in eqn.(2), synthetic NMO corrected gathers were generated (Fig.3). It is observed that the peaks and troughs of zero phase gather are directly related to increasing and decreasing impedance contrasts respectively. In case of minimum phase wavelet, they do not correspond exactly to sharp contrasts. Zero phase NMO corrected synthetic gather clearly shows the anomalous amplitude behaviour corresponding to tops of pay sands 2 and 4. The response for pay sands 1 and 3 is not very distinct due to their small thickness and as a result they generate composite response with the base of pay sands 2 and 4 respectively. The synthetic NMO corrected gathers were utilized for the extraction of AVO attributes, the intercept (A), and the gradient (B) or (slope) using straight-line least-square fit method.

For comprehensive, at the glance understanding and analysis of various AVO anomaly trends, a display panel consisting of NMO corrected gather, $A*B$ product (variable

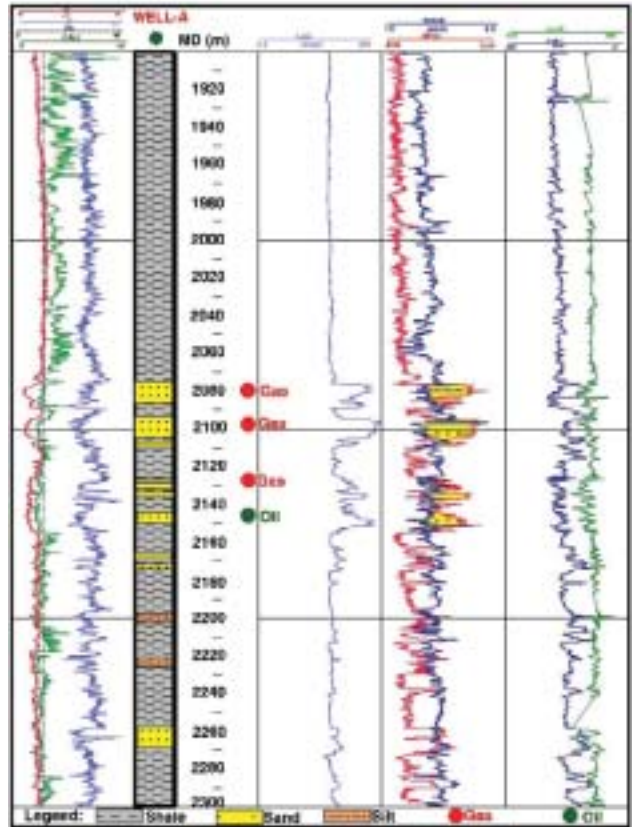


Fig.1.: Sample logs and litho-column of well-A

intensity in colour with intercept (A) in wiggle trace), A-B cross-plot and a colour coded intercept seismic trace with demarcated cross-plot zone in A-B cross-plot has been made. The display panels corresponding to zero and minimum phase NMO corrected synthetic gathers at well-A are shown in Figs.4 (a,b) respectively. The grey ellipse denotes background trend. Under a variety of reasonable geologic circumstances A's and B's for brine saturated sandstones and shales follow background trend. AVO anomaly trend is coloured in orange and blue. They are properly viewed as deviations from the background trend and are related to presence of gaseous hydrocarbons. This panel clearly shows that the AVO cross-plot is having less random scatters, AVO anomalies have higher amplitude strength, represent type 2/3 classes and they are much better defined in case of zero phase data than minimum phase. The effect of phase variation is also examined in real NMO corrected seismic gathers near the well-A. A super gather was generated using trace by trace averaging of five consecutive gathers. A wavelet was extracted from the super gather by semi-deterministic method. Real NMO corrected gather was dephased to get zero phase output with the help of extracted wavelet. The calibrated NMO corrected real CDP gathers with original phase and

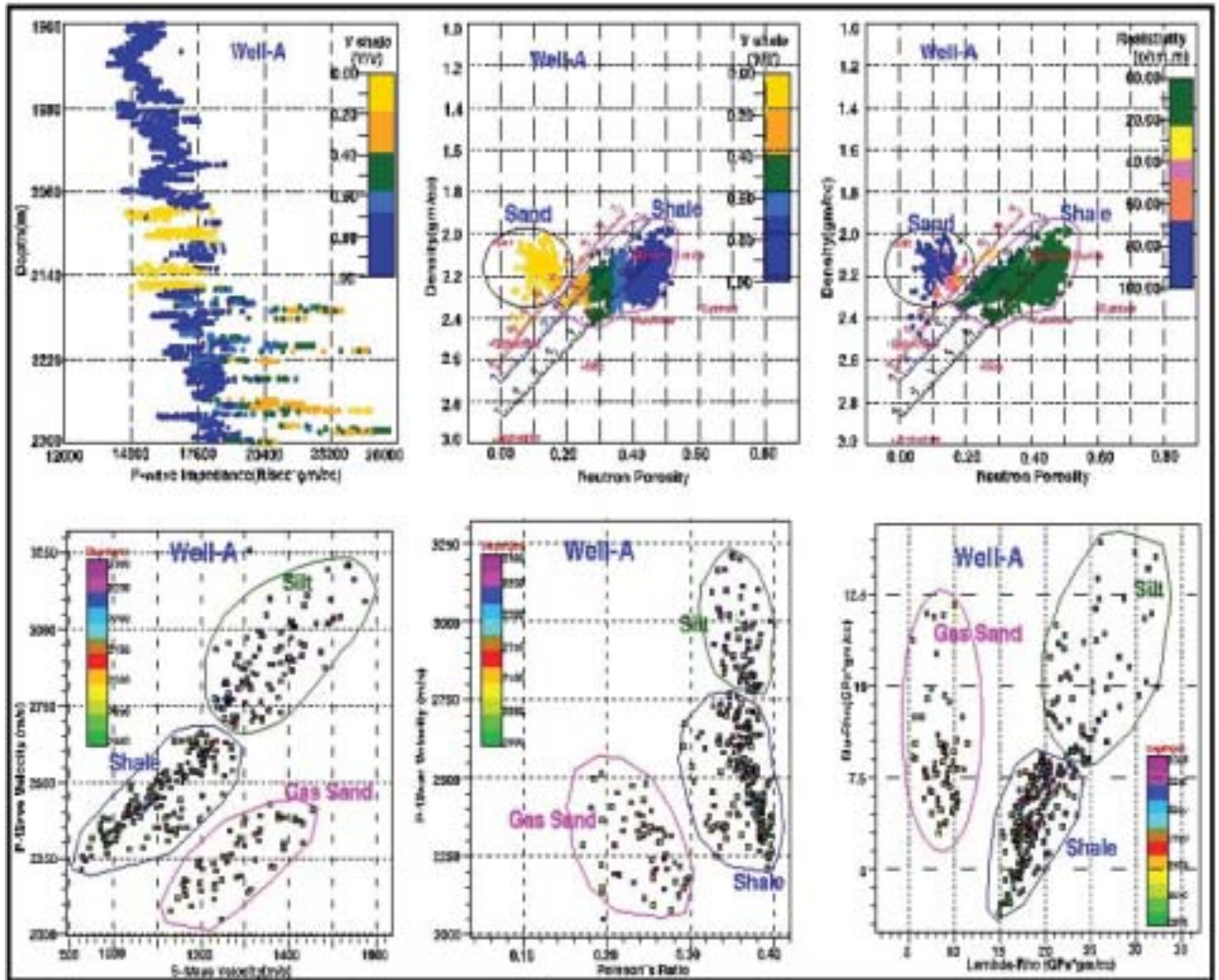


Fig.2(a-f): Cross-plot analysis using different logs of well-A

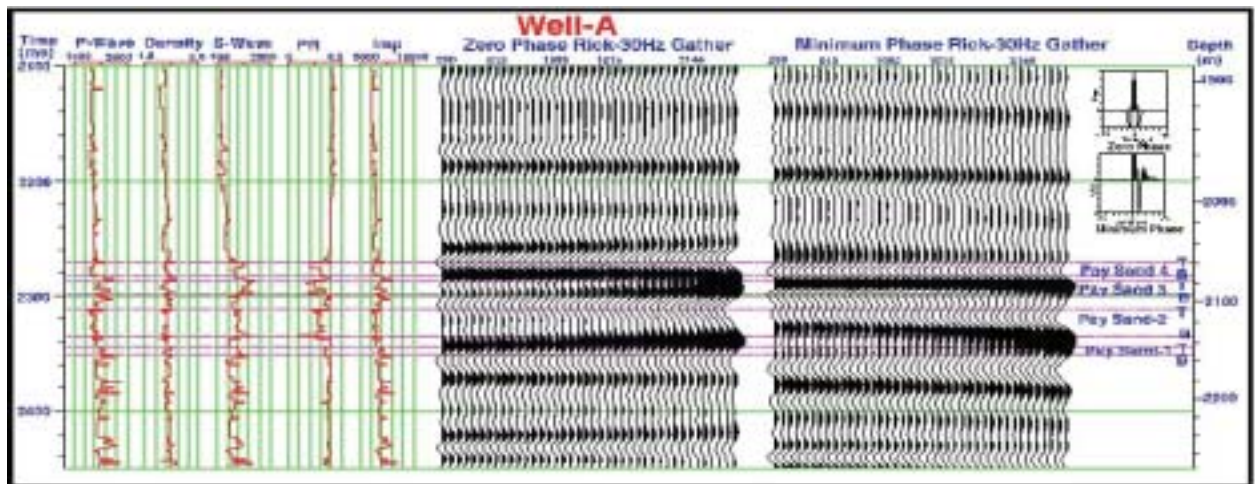


Fig.3 : Synthetic gathers generated with 30 Hz zero and minimum phase Ricker wavelets

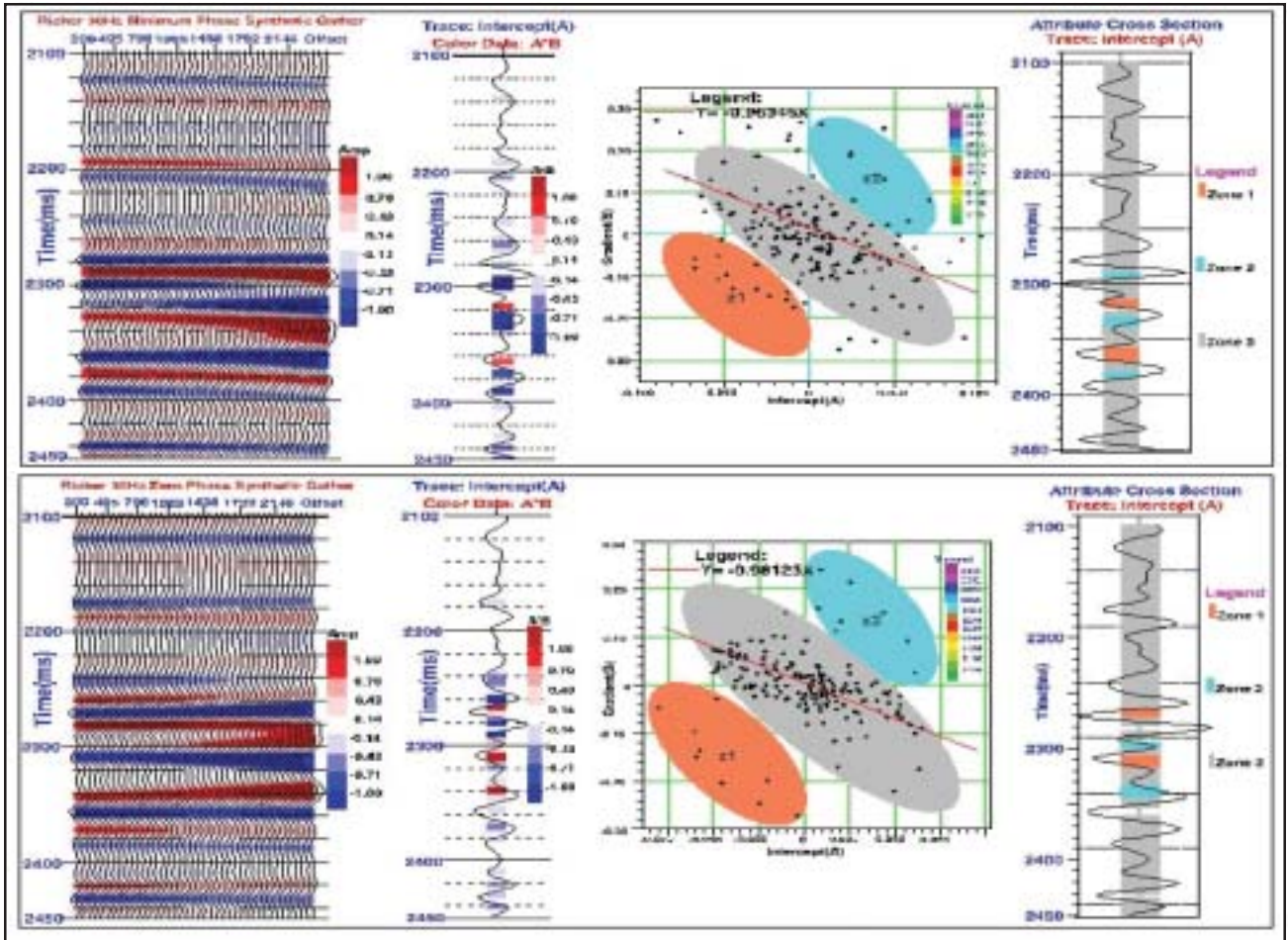


Fig4(a,b): Display panels showing AVO attribute A*B and their cross-plot generated from 30Hz minimum and zero phase synthetic gathers.

after zero phasing are shown along with log data (Fig. 5). A similar study as done in case of synthetic gathers has been again carried out using these real gathers. AVO attributes display panels similar to synthetic gathers are shown in Fig.6(a,b) which again confirms the observations as seen in the synthetic gathers.

In the example discussed below an exploratory well was planned to be drilled in the same area where well-A was drilled. The stack seismic data at the target zone exhibits bright spot anomaly (Fig.7a). Five NMO corrected original gathers in the bright spot area are shown in Fig.7b). To confirm the fluid type present in the reservoir, AVO analysis was attempted. As means for wavelet estimation were not available, phase rotation technique was adopted. For reducing the phase variation of NMO corrected gathers and bring them close to zero phase prior to AVO analysis, phase rotation test was conducted on a original NMO corrected super gather (generated by trace by trace averaging of consecutive 5 gathers). Phase rotation in 30

degree steps was performed. The basic AVO attributes were computed using the original and phase rotated super gathers. It has been observed that the crossplot generated from the super gather rotated by 90 degree show clear class2/3 types AVO anomaly than the original super gather (Fig8a,b) indicating closeness with zero phase. Further for developing higher confidence, 21 amplitude preserved NMO corrected gathers close to area of interest were taken and they were phase rotated in 30 degree steps as it was done for super gather. From these rotated gathers, basic AVO attributes were generated and cross-plotted (Fig.9(a-i)). Among these, A-B cross-plot generated from 90 degree phase rotated gathers show clear cut class2/3 AVO anomaly and data points are symmetrically deviated in respective quadrants from the background trend. This deviation was interpreted as presence gas charged low impedance reservoirs in the target zone.

To demonstrate the robustness of phase rotation

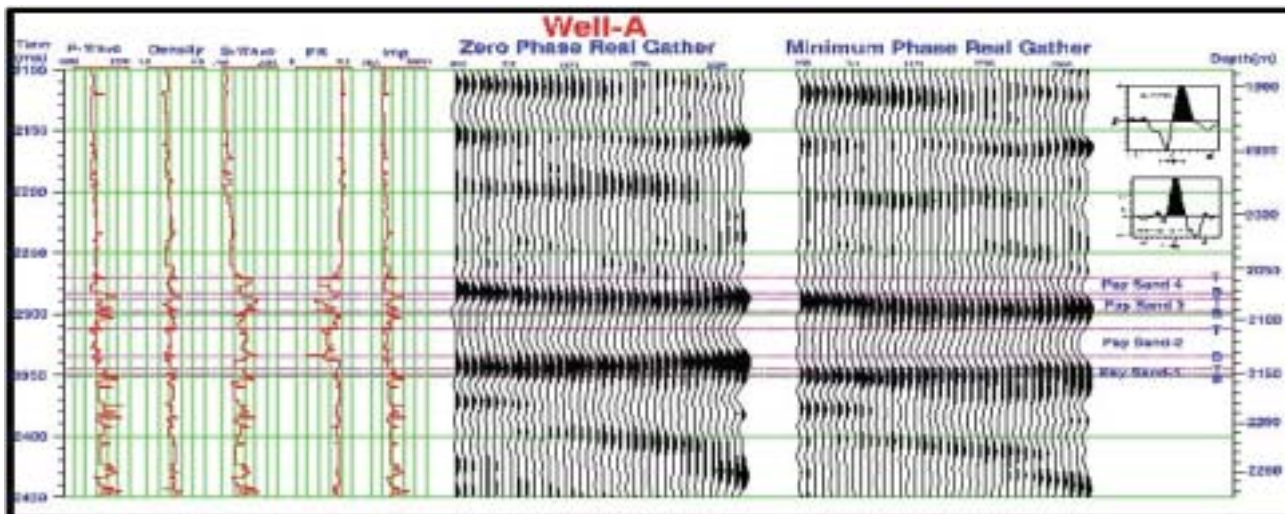


Fig.5: Display of logs, original real and dephased gathers at Well-A. The wavelets extracted from original real gather by semi-deterministic method and extracted from dephased gathers are also shown.

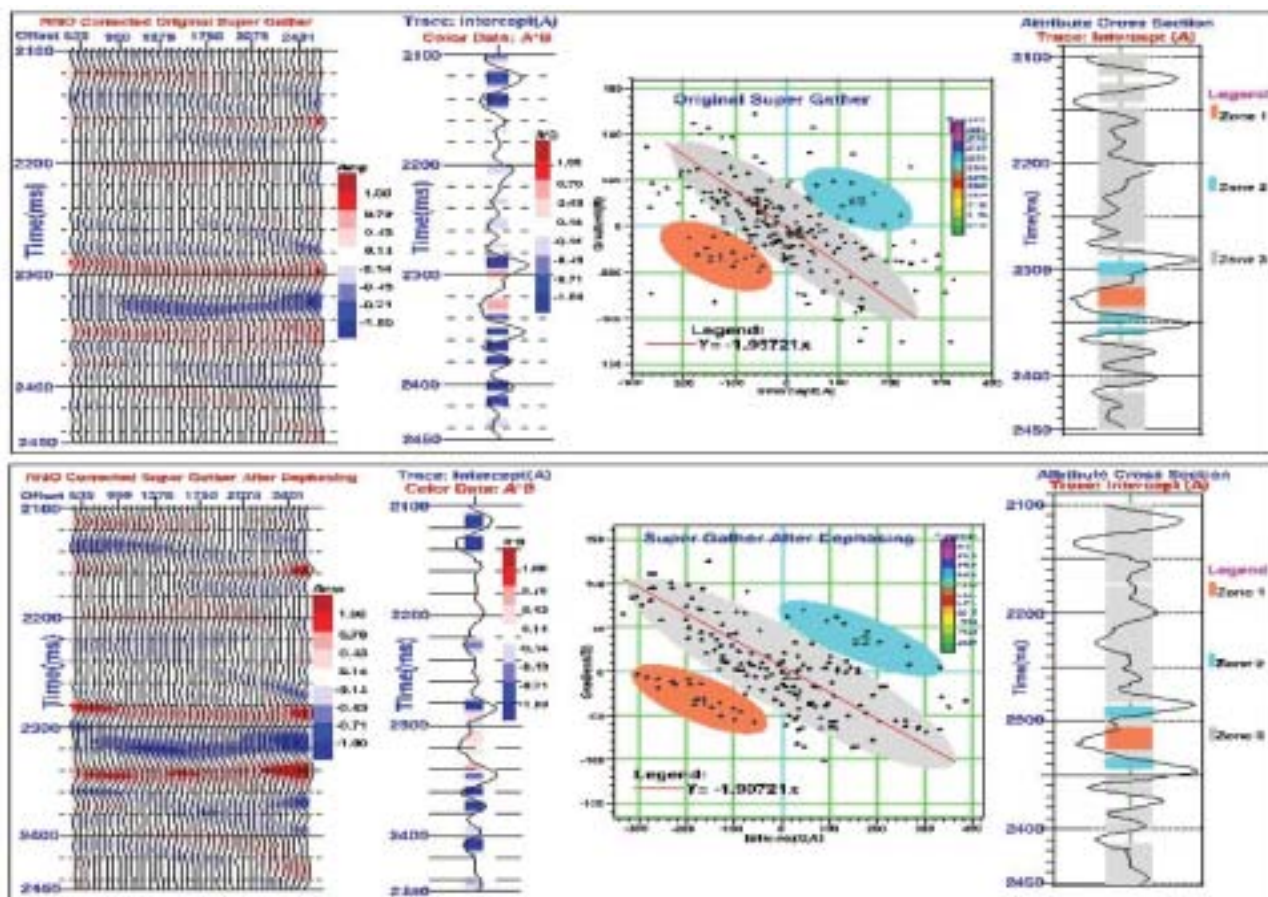


Fig6 (a,b): Display panels showing AVO attribute A*B and their cross-plot generated from real and dephased super gathers at well-A.

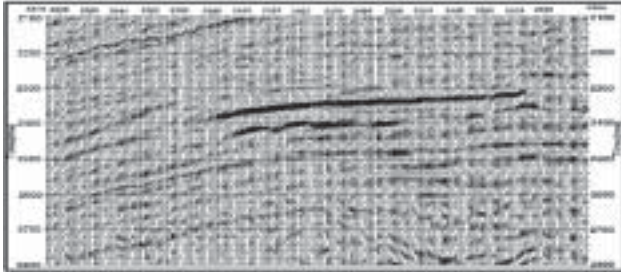


Fig.7a: Seismic section showing bright spot on stack data

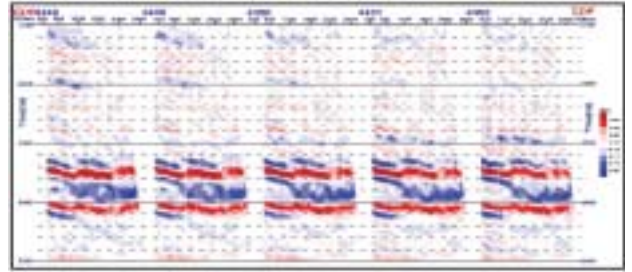


Fig.7b: Five NMO corrected gathers close to bright spot anomaly

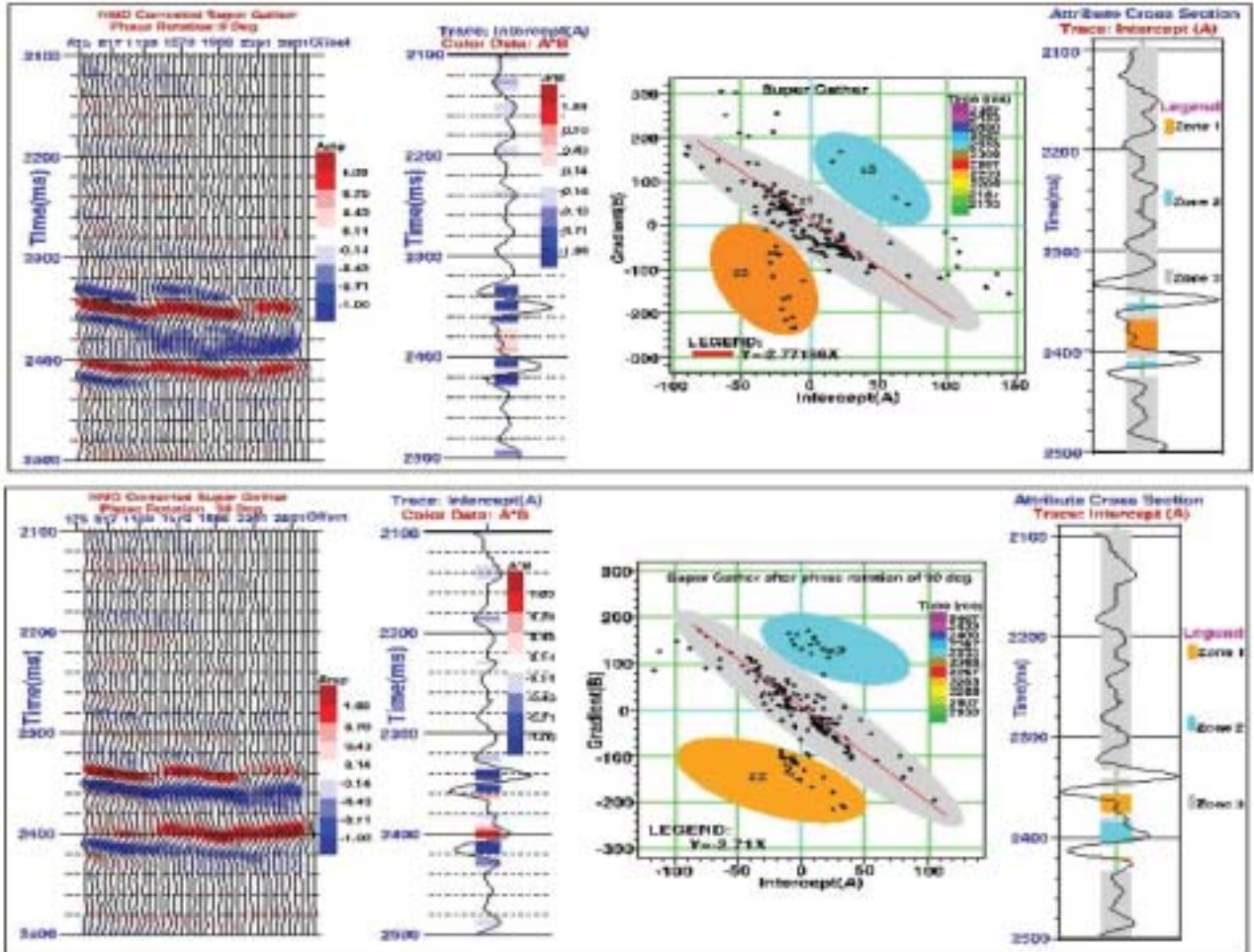


Fig.8(a,b): Display panels showing AVO attribute $A*B$ and their cross-plot generated from real and 90 degree phase rotated super gathers close to bright spot anomaly.

technique for AVO analysis a dry well-B was taken up. The sample logs along with lithology of this well are shown in Fig(10a). A display of five real NMO corrected CDP gathers close to well-B are shown in Fig.(10b). AVO modelling carried out at well-B does not show any AVO anomaly in synthetic minimum and zero phase NMO corrected gathers (Fig.10c). The display panel of zero phase synthetic gather has been shown in (Fig.10d) does not show any anomalous AVO

behaviour and all the data points are falling in back ground trend of A-B cross-plot. The cross-plot for zero phase synthetic and a super gather were generated which do not show any AVO anomaly (Fig11a,b). A phase rotation in 30 degree steps was applied in 21 amplitude preserved NMO corrected gathers close to well-B. From these rotated gathers, basic AVO attributes were generated and cross-plotted (Fig.11c-i). These cross-plots do not show any AVO anomaly

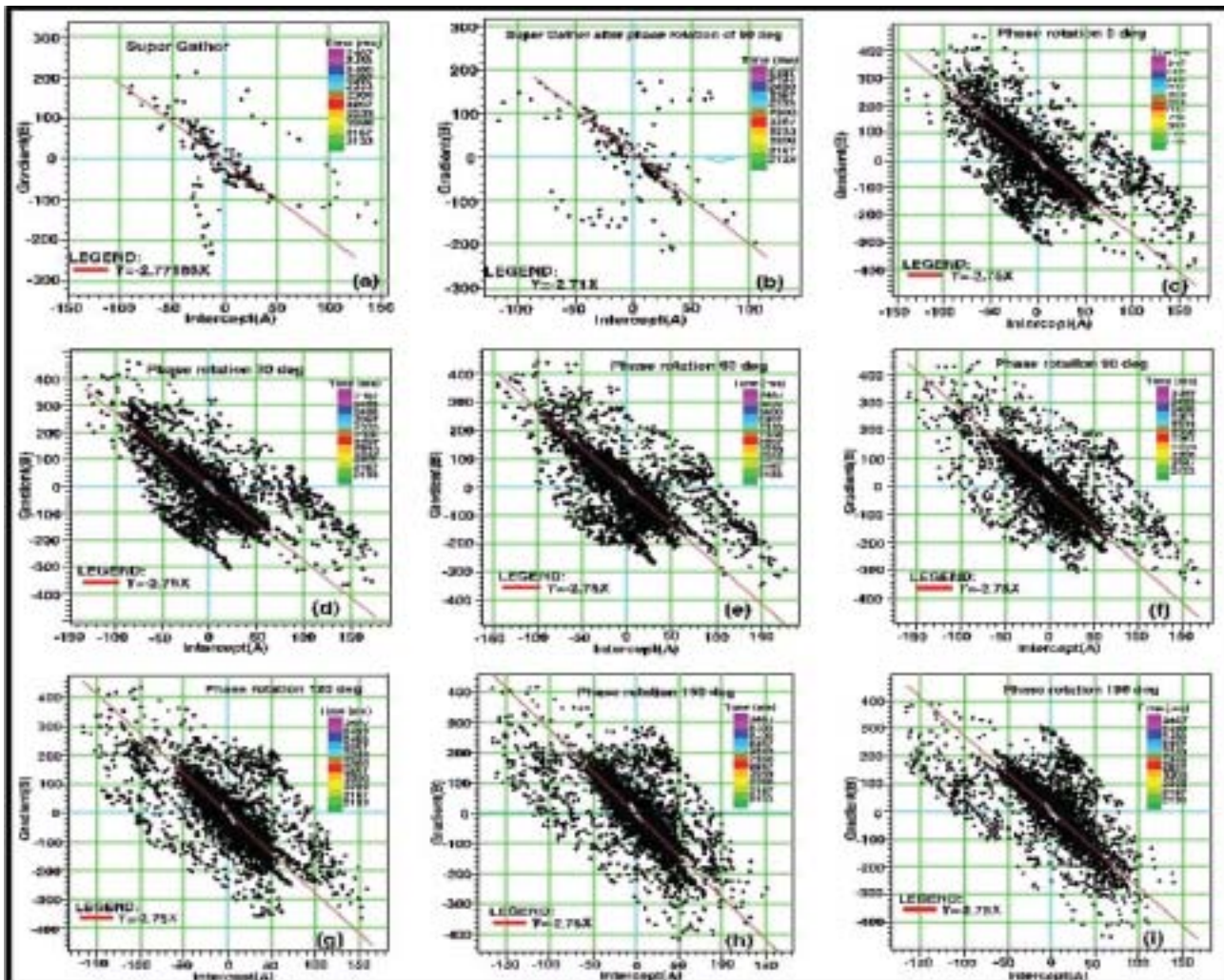


Fig.9: A-B Cross-plots of (a) original real gather (b) 90 degree phase rotated super gather and (c-i) A-B crossplots for phase rotated 21 NMO corrected gathers in 30 degree steps

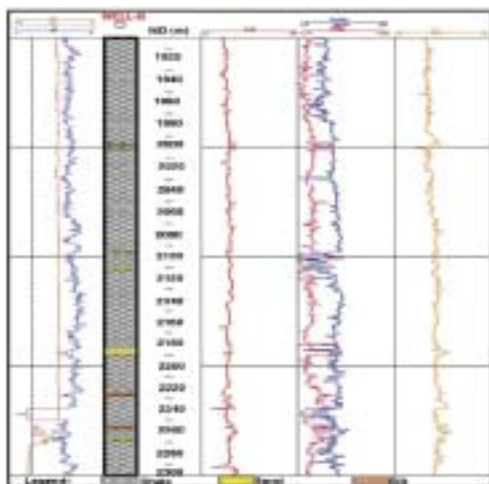


Fig.10a.: Sample logs and litho-column of well-B

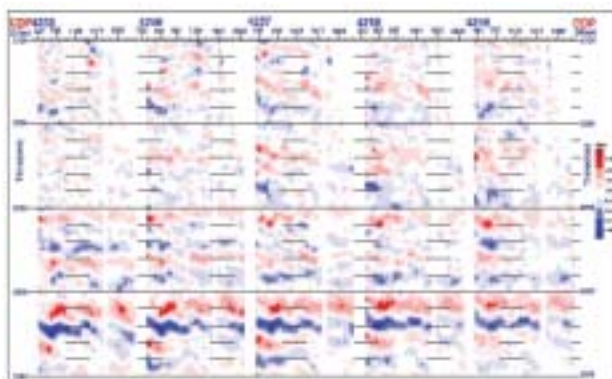


Fig.10b: Five NMO corrected gathers close to well-B

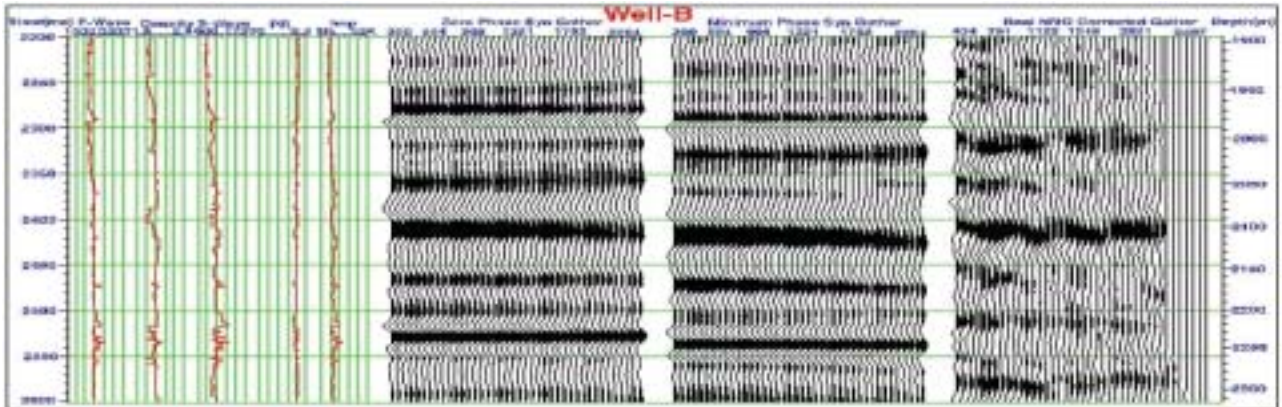


Fig.10c: Display of logs , synthetic zero and minimum phase gathers along with original real gather at Well-B. The wavelet extracted from original real gather by semi-deterministic method was used generating synthetic gathers.

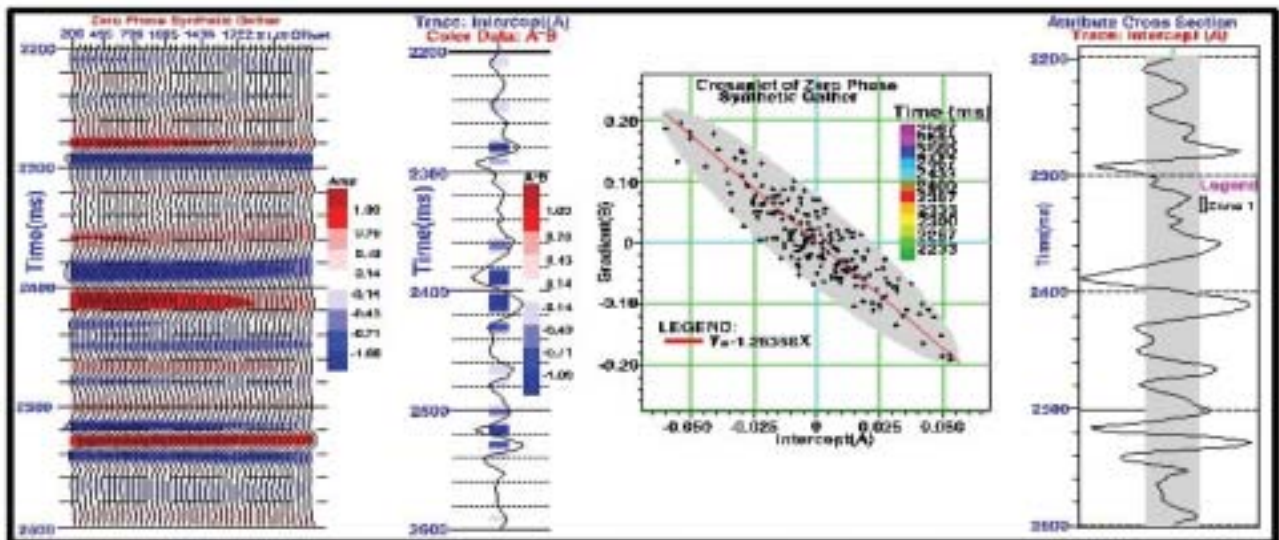


Fig10d: Display panels showing AVO attribute $A*B$ and their cross-plot generated from zero phase synthetic NMO corrected gather at well-B

and confirms the robustness of phase rotation technique. Based on this work an exploratory well-C was drilled which was found hydrocarbon bearing in the zone of interest. A litho-column along with sample logs and a seismic section showing the target zone is shown in Fig,(12a,b). The results of this study amply demonstrate the efficacy of adopted quantitative AVO analysis approach.

Conclusions

AVO attributes cross plotting of modelled seismic data derived from well logs for minimum and zero phase wavelets provides a strong foundation for understanding the impact of phase variations on Quantitative AVO analysis. The modelling study has further reconfirmed the superiority of zero phase over minimum phase amplitude preserved NMO corrected CDP gathers for successful AVO analysis and

improved seismic interpretation. In case of exploratory situations, phase rotation of seismic gathers and their analysis can provide improved understanding about the type of AVO classes and their interpretation. Based on the methodology adopted in this work for AVO analysis, one exploratory location was drilled and gaseous sand reservoir was encountered in the target zone. This study emphasises that quantitative AVO analysis has the ability to illuminate prospects that might have been masked in the background trend due to phase variations.

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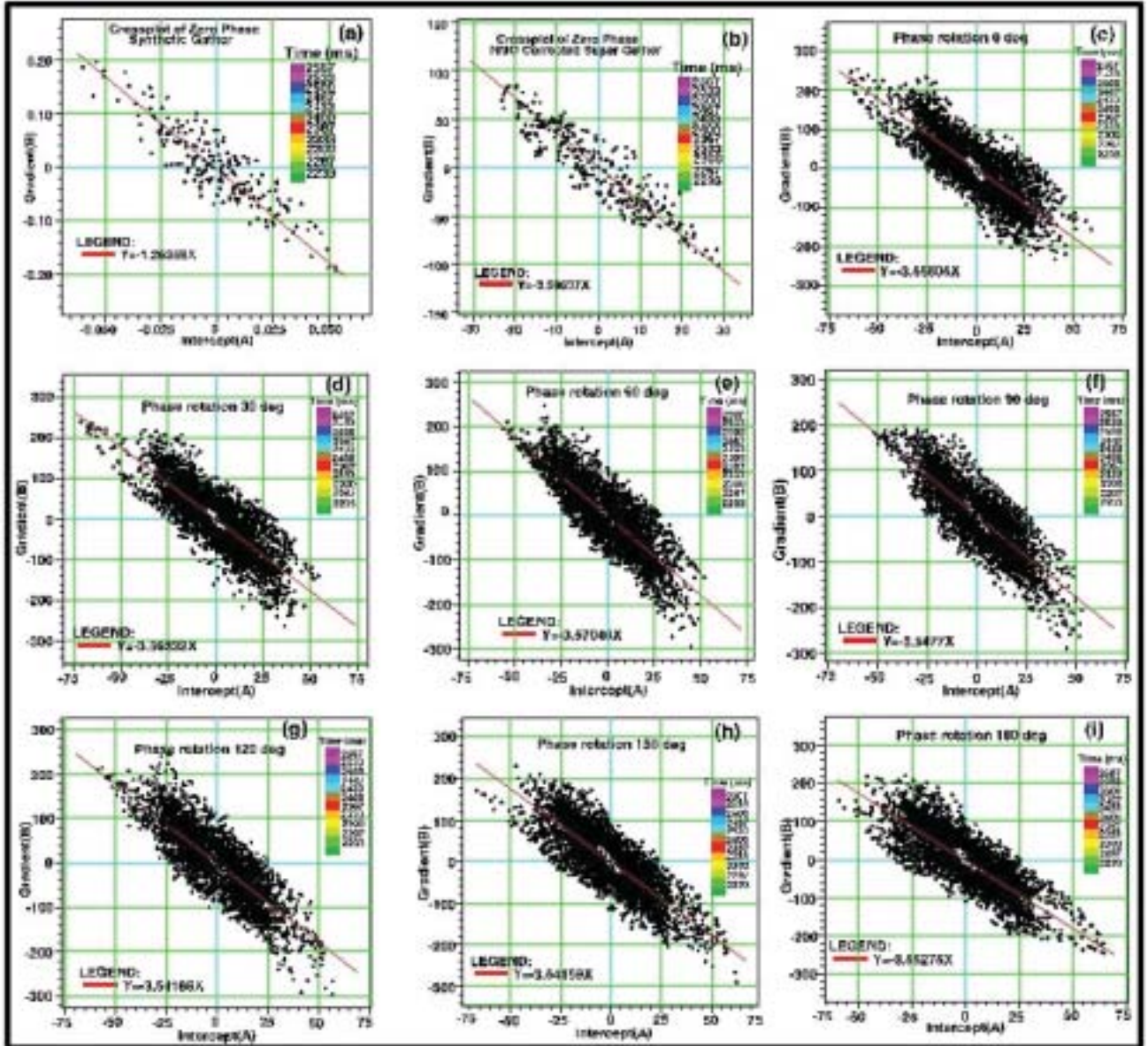


Fig.11: A-B Cross-plots of (a) zero phase synthetic gather (b) zero phase super gather and (c-i) A-B crossplots for phase rotated 21 NMO corrected gathers in 30 degree steps

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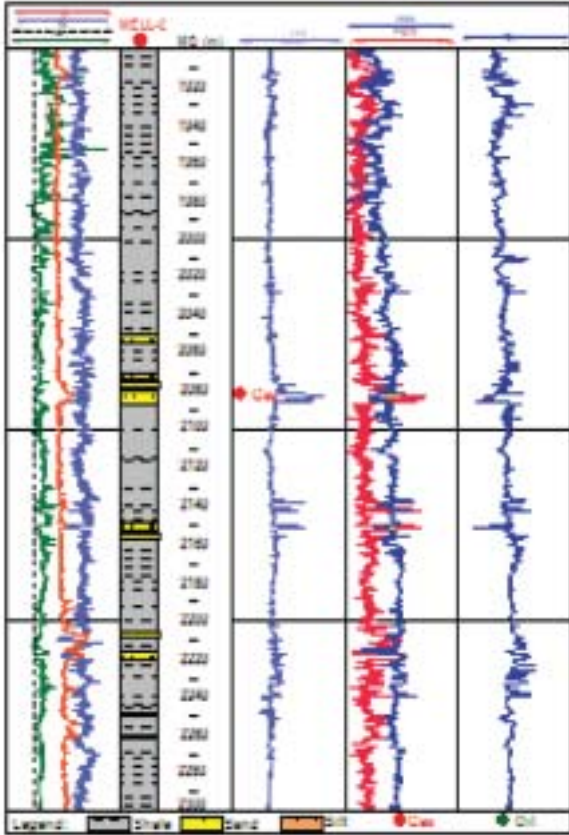


Fig.12a.: Sample logs and litho-column of well-C

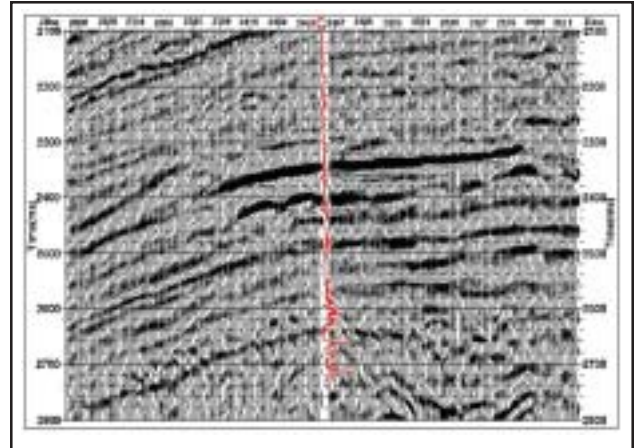


Fig.12b: Seismic section with inserted P-wave curve at well-C gathers at well-A.

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