INTERNATIONAL JOURNAL OF NATURAL AND APPLIED SCIENCES (IJNAS) , VOL. 2, NO. 1(2007); P. 65 – 73, 2 TABLES, 7 FIG.

A simple review of amplitude variation with offset (AVO) analysis as a direct gas indicator (DGI).

O. O. Olagundoye[*1], C. S. Okereke[1], E. U. Egeh[1] and D. A.Obi[1].

ABSTRACT

A major risk in the use of the Bright Spot Technique in natural gas detection is the possibility that the anomalous amplitude zone or bright spot identified on seismic reflection data may contain little or no gas. This is because igneous intrusions, carbonate or hard streaks, coal beds, and wet sands often show up on seismic data as bright spots. The anticipated impact of any sudden shortage of oil and/or gas on economies and way of life underscores the value of effective hydrocarbon exploration around the world. Currently, strong gas prices and increases in global gas consumption, and the trend towards the much talked about 'methane age' have led to a focusing of oil industry attention on gas exploration opportunities and more efficient gas detection technologies. One of such technologies is AVO analysis; a seismic analysis technique that searches for direct gas indications using the amplitudes on pre-stack seismic data. In this presentation, we present a simple review of the AVO technique with the aim of providing a framework for easy and better understanding of this seismic interpretation technique as a technology in the direct identification, and appraisal of gas prospects.

INTRODUCTION

Purpose of review

The envisaged impact of any sudden shortage of oil and/or gas on economies and way of life underscores the value of effective hydrocarbon exploration around the world. In the past couple of years, strong oil and gas prices have led to a focusing of oil industry attention on exploration opportunities. However, the ever increasing global gas consumption and trend towards the much talked about 'methane age' is expected to tilt the balance towards natural gas exploration. No technical factor may be as important in governing the future supply of conventional oil and gas as the development of improvements in geophysical techniques (Dobrin and Savit, 1988). One of these developments is the direct detection of gaseous hydrocarbons through techniques hinged on the interpretation of properly processed seismic attributes (such as frequency, wavelength, amplitude, etc.) evident on reflection data. These techniques include, bright spot, amplitude variation with offset (AVO), Amplitude variation with angle (AVA), amongst others. This paper provides a simple review of the principles, procedures, and limitations of the AVO technique in direct gas identification. In this presentation, applications of AVO analysis in gas detection and appraisal in various basins are cited to demonstrate the practicability of AVO interpretation techniques in detecting gas on seismic reflection data. It is expected that the present review would provide a framework for easy and better understanding of the predictive ability of the AVO technique.

Historical account

The discovery of high-amplitude reflections (i.e. bright spots) produced by in-situ gas in reservoirs in the 1960s led to the development in the early 1970s of the then widely acclaimed bright spot technique. this technique is based on the principle that an anomalously high amplitude seismic reflection event is produced when there is a greater contrast in velocities at an interface when one formation is charged with gas than when the same formation is saturated with oil or water. In young clastic basins (such as the offshore Gulf of Mexico, Niger Delta, etc.), natural gas exploration with this technique has been quite successful. The bright spot technique, however, has limitations- seismic interpreters can be deceived when certain shale masses, non-commercial gas accumulations at anomalously high pressure, facies changes, geometric focusing effects, igneous intrusions, carbonate or hard streaks, lignites (coal beds), and wet sands show up on seismic as bright spots (Dobrin and Savit, 1988; Shirley, 1995).

Consequently, one of the major risks in the use of the bright spot technique is that the anomalous zone identified on seismic reflection data may contain little or no gas.

[*]Corresponding author. Email: bosolare@yahoo.com
Manuscript received by the Editor September 28, 2004; revised manuscript accepted July 17, 2006.
[1]Onshore Assets – GSR, Total E & P Nig. Ltd., Port Harcourt, Nigeria.
[2]Department of Geology University of Calabar ,Calabar, Nigeria

This exploration risk can be reduced by employing a direct gas detection technique that can distinguish between ‘gas and non-gas anomalies’ on seismic sections. The resulting search for a more definitive direct gas indicator (DGI) on a seismic section than bright spots led to the development of the AVO technique in the early 1980s. According to SPDC (1999), it is considered to be one of the techniques of verifying whether a bright spot is really a gas anomaly. Amplitude variation with offset (AVO) analysis is a particular type of seismic attribute analysis that measures variations in the Poisson’s ratio (P- wave velocity/S- wave velocity) of different rock formations and consists of examining the amplitude of a reflection with increasing angle of incidence, or source receiver distances or offsets (SPDC, 1999). It is a seismic technique that searches for direct gas indicators (DGIs) using the amplitudes of pre-stack seismic data, and is also referred to as “amplitude versus offset analysis’’. It may also be regarded as the study of the relative amplitudes of traces within a CMP gather. This study of relative amplitudes attempts to relate changes in seismic amplitudes with changes in the reflection coefficient (RC) series or geology. Such a relation is however based on the assumption that effects from the other two controlling factors of trace amplitudes (i.e. the seismic wavelet, and its interactions through convolution) have been estimated and removed during seismic data processing. Although the removal of such effects to obtain absolutely true amplitudes is impossible, relative changes in amplitude have been shown to be adequate in direct hydrocarbon identification and lithofacies estimation (Skaarup et al., 2000; Henry, 2004).

Advantages of AVO analysis

AVO analysis has gained widespread attention among hydrocarbon explorationists because, it

(i) facilitates the direct identification of gas with more confidence by overcoming the limitations of the Bright Spot Method, without making an S- wave recording,

(ii) facilitates the pining down of subtle stratigraphic targets,

(iii) is a robust and inexpensive method for identifying potential reservoirs when applied to 3D seismic data,

(iv) adds an extra dimension to studies done only with stacked seismic data,

(v) is useful in the choice of optimum well locations for increased drilling success ratios,

(vi) may be employed in fracture detection (i.e. discrimination between gas- and fluid-filled crack systems) through the use of azimuthal variations in recorded reflection amplitudes resulting from increases in the absorption coefficient of the earth,

(vii) facilitates the seismic signature delineation of lithology, through the matching of rock properties extracted from seismic (CDP gathers) response with lithology, and

(viii) requires little or no extra acquisition effort since its major input data, the common midpoint (CMP) gather (i.e. the set of traces sampling the same subsurface point at varying offsets), is an integral part of modern seismic data acquisition; a probable reason why AVO analysis is often regarded as the study of the relative amplitudes of traces within a CMP gather is also known as Amplitude Variation With Offset Analysis.

PRINCIPLES OF THE AVO TECHNIQUE

The mathematical foundation of the AVO technique (Fig. 1) is embodied in the Zoeppritz’s equations (Fig. 2), which give the reflection and transmission coefficients for plane waves as a function of angle of incidence (θ) and six independent elastic parameters, three on each side of the reflecting interface (Fig. 1). These elastic parameters are P- wave velocities (V_{p1} and V_{p2}), densities (ρ_1 and ρ_2), and Poisson’s ratios (σ_1 and σ_2). Essentially, the Zoeppritz’s equations describe the relations of incident, reflected and transmitted longitudinal waves (P- waves) and shear waves (S- waves) on both sides of an interface (Smith and Gidlow, 1987). Approximations to the Zoeppritz’s equations have been made by Bortfield (1961), Aki and Richards (1980), and Shuey (1985). These approximations are simplifications which describe the variation of P- wave reflection coefficients (R_p) with the angle of incidence (θ) of a P- wave, as a function of the P- wave velocities (V_{p1} and V_{p2}), S- wave velocities (V_{s1} and V_{s2}), and the densities above and below a seismic interface (ρ_1 and ρ_2). Generally, based on these approximations of the Zoeppritz’s equations, P – wave reflection coefficient (R_p) as a function of angle of incidence may be expressed in the form (Fig. 3),

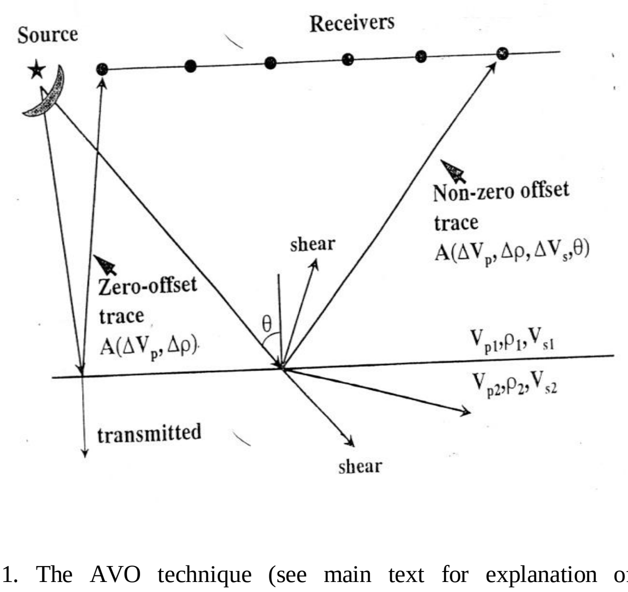


Fig..1. The AVO technique (see main text for explanation of variables).

$\sin\theta$	$\cos\varphi$	$-\sin\theta'$	$\cos\varphi'$	R_p	$-\sin\theta$
$-\cos\theta$	$\sin\varphi$	$-\cos\theta'$	$-\sin\varphi'$	R_s	$-\cos\varphi$
$\sin 2\theta$	$\frac{V_{p1}}{V_{s1}}\cos 2\varphi$	$\frac{\rho_2 V_{s2}^2 V_{p1}}{\rho_2 V_{s1}^2 V_{p2}}\sin 2\theta'$	$\frac{\rho_2 V_{s2} V_{p1}}{\rho_1 V_{s1}^2}\cos 2\varphi$	T_p	$\sin 2\theta$
$\cos 2\theta$	$-\frac{V_{s1}}{V_{p1}}\sin 2\varphi$	$-\frac{\rho_2 V_{p2}}{\rho_1 V_{p1}}\cos 2\theta'$	$-\frac{\rho_2 V_{s2}}{\rho_1 V_{p1}}\sin 2\varphi'$	T_s	$-\cos 2\varphi$

Fig. 2. Matrix representation of the Zoeppritz's equation (see main text for explanation of variables)

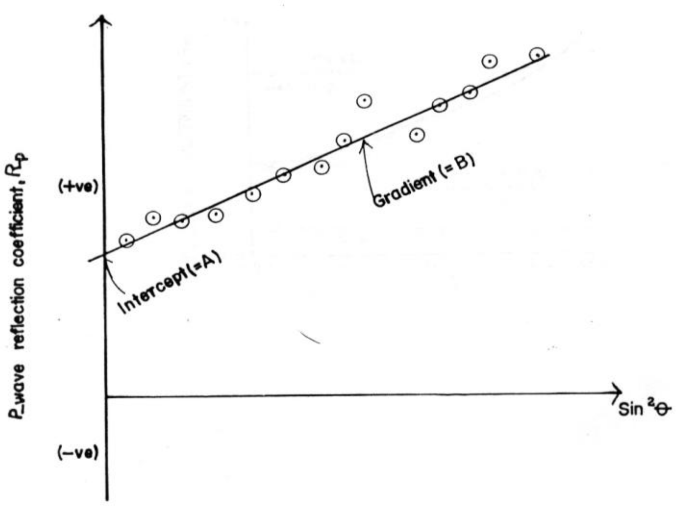


Fig. 3. Graphical relationship between P- wave reflection coefficient (R_p) and angle of incidence (θ).

$$R_p(\theta) = A + B\sin^2\theta \quad (1)$$

where A is the AVO intercept and B is its gradient. In practice, A is the band-limited measure of the normal incidence amplitude and may also be regarded, assuming amplitude calibration, as the normal incidence reflection coefficient (Castagna and Swan, 1997). Similarly, B is a measure of amplitude variation with offset. According to Castagna and Swan (1997), B is also a measure of offset-dependent reflectivity.

In simple terms, Equation 1 underscores the angular dependence of P- wave reflection coefficients on AVO intercept and gradient.

For the expression in Equation 1, B is given as

$$B = \left[-\frac{2V_s^2}{V_p^2}\frac{\Delta\rho}{\rho} + \frac{1}{2}\frac{\Delta V_p}{V_p} - 4\frac{V_s^2}{V_p^2}\frac{\Delta V_s}{V_s}\right] \quad (2)$$

with, $$V_p = \frac{(V_{p2} + V_{p1})}{2}, \quad (3)$$

$$V_s = \frac{(V_{s2} + V_{s1})}{2}, \quad (4)$$

$$\rho = \frac{(\rho_2 + \rho_1)}{2}, \quad (5)$$

$$\Delta V_p = V_{p2} - V_{p1}, \quad (6)$$

$$\Delta V_s = V_{s2} - V_{s1}, \quad (7)$$

$$\Delta\rho = \rho_2 - \rho_1, \quad (8)$$

where,

V_{p2} = P- wave velocity in underlying medium,

V_{p1} = P- wave velocity in overlying medium,

V_{s2} = S- wave velocity in underlying medium,

V_{s1} = S- wave velocity in overlying medium,

ρ_2 = density of underlying medium, and

ρ_1 = density of overlying medium.

Elaborate mathematical analyses leading to approximations to the Zoeppritz's equations can be found in Bortfield (1961), Aki and Richards (1980), and Shuey (1985).

The central point in AVO analysis is that the AVO gradient (B) responds to both P- and S- wave reflections from an interface. It is this behaviour that is used to locate gas charged reservoirs in direct hydrocarbon identification. To fully understand this, one must remember that a seismic recording measures two- way travel times to a particular geological interface and the reflection amplitude. However, the maximum size or amplitude of this seismic reflection varies with offset. The magnitude of these variations depends on how suddenly the velocity, density, or other subsurface rock and fluid properties change from one layer to another (Sickle and Valusek, 1990).

The use of AVO as a direct gas detector is based on the differences in the response of P- wave and S- wave velocities (V_p and V_s) of a reservoir rock to the gas in its pore spaces. S- waves in contrast to P- waves do not see the pore spaces of a rock and thus have a velocity that depends mainly on rock matrix. Air or gas in a reservoir's pore spaces can lead to a drastic reduction in P wave velocity, with relatively no reduction in S wave velocity. This leads to a decrease in Poisson's ratio (V_p/V_s) which in turn changes the relative amplitudes of the top- and base- reflections of the reservoir as a function of angle of incidence (θ) at which the seismic wave impinges on the boundaries (Fig. 4). Consequently, the partitioning of an incident seismic wave differs for a gas-sand/shale (or gas-sand/wet sand) reflector, and most other reflectors. These reflection amplitude variations relative to other reflections may be observed as an increase or decrease with offset (see Equation 1; Figs. 1 and 4) depending on subsurface conditions. This increase or decrease is an anomalous seismic response that AVO is aimed at identifying. Figure 4 shows the variations of reflection amplitude with offset for a gas and a water sand. Table 1 is a chart summarizing the AVO behaviour of various gas- sand classes.

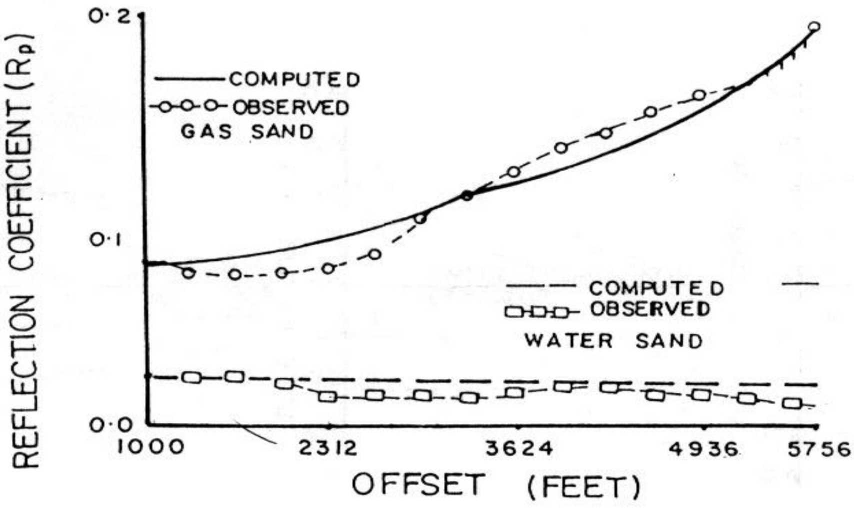
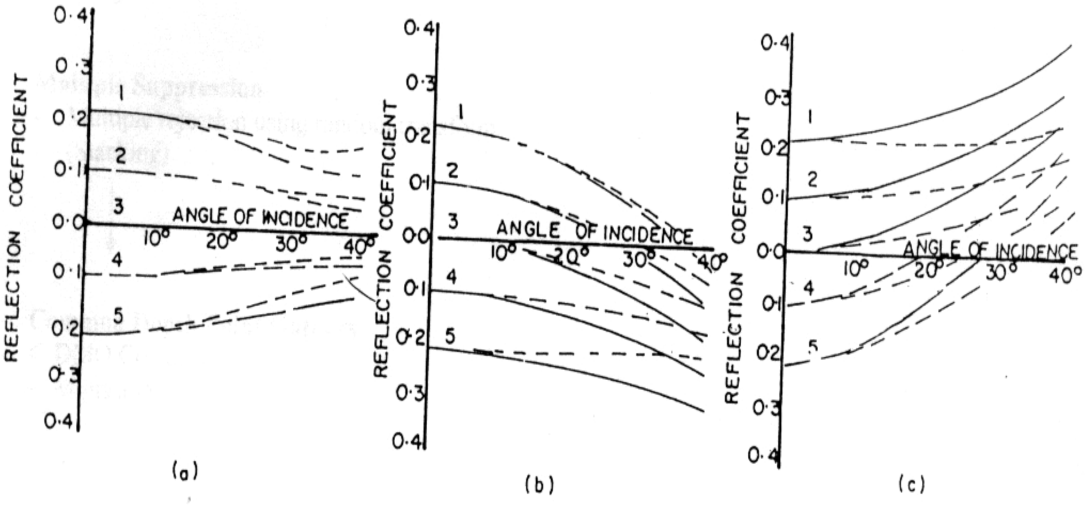


Fig. 4. Variation of amplitude with offset for a gas- and a water-sand (After Yu, 1985).



(a) No change in Poisson's ratio
(b) Decreasing Poisson's ratio
(c) Increasing Poisson's ratio
(After SPDC, 1999).

Fig. 5. Variations of P-wave reflection coefficient (R_p) with angle of incidence (θ).

Table 1: Chart summarizing the AVO behaviour of various classes of gas sands (After Castagna and Swan, 1997).

CLASS	RELATIVE IMPEDANCE	QUADRANTS	A	B	AMPLITUDE versus OFFSET
I	Higher than overlying unit	IV	+	-	Decreases
II	About the same as the overlying unit	II, III, or IV	+ or -	-	Increase or decrease; may change sign
III	Lower than overlying unit	III	-	-	Increases
IV	Lower than overlying unit	II	-	+	Decreases

Three possible AVO responses (Fig. 5) exist for practical reflection cases:

1reflection amplitude decrease(s) with increasing angle of incidence regardless of reflection coefficient polarity, for little change in Poisson's ratio (Fig. 5a).

Reflection amplitude increase(s) with angle of incidence for,

A negative reflection coefficient polarity and decrease in Poisson's ratio (such as for the top of a gas sand embedded in a shale, etc.; Fig. 5b)

A positive reflection coefficient polarity and increase in Poisson's ratio (such as for the base of a gas sand embedded in a shale, gas/water contact, etc.; Fig. 5c), and initial reflection amplitude decrease(s) with angle of incidence, followed by waveform polarity reversal and reflection amplitude increase(s) with opposite polarity, for, a positive reflection coefficient polarity and a decrease in Poisson's ratio (Fig. 5b), or a negative reflection coefficient polarity and an increase in Poisson's ratio (Fig. 5c).

GENERAL PROCEDURE FOR AVO ANALYSIS

The application of AVO analysis to direct gas identification involves several areas of effort such as data acquisition, processing, and interpretation. Efficient data acquisition programmes and greater intergration between data processing and interpretation efforts enhance the effectiveness of AVO analysis as an exploration tool.

Data acquisition

Data acquisition for a typical AVO analysis scheme may be 2-D (conventional) or 3 D. Acquired data may be land- or marine- derived. The inherent advantages of 3-D seismic data over conventional seismic data have made it a standard dataset for AVO analysis. However, there is some scepticism amongst geophysicists on the worth of using AVO analysis on 3D land surveys. Seismic data acquired in typical 3D land exploration programmes is generally considered less suitable than 3D marine data for detailed AVO studies due to limitations in offset ranges, lower signal/noise ratios (SNR), and problems with surface consistent amplitude variations. However, short period multiples in 3D land- acquired seismic data are not very troublesome during AVO analysis when compared with 3D marine data. Methods such as signal processing and the limitation of AVO imaging to the zone of interest may be used to a certain degree in overcoming problems with different sources and receivers, statics and noise, and problems associated with offset distribution respectively prior to applying AVO analysis on 3D land data.

Data processing

Fig. 6 presents the basic processing flow for signal processing of a typical 3D seismic land data set to preserve true amplitudes prior to AVO analysis. The processing flow for a marine data set differs slightly, incorporating more emphasis on multiple removal and less on improvements in SNR (Allen and Peddy, 1993). The dependence of AVO analysis on offset sufficiency on acquired seismic data makes the determination and attainment of offset sufficiency on seismic data the primary objective in any processing scheme for AVO analysis. Primarily, the processing goal is the attainment of sufficient offset in seismic data that would facilitate the analysis of offset dependence of reflection amplitude. Although the linearization of Zoeppritz's equation is only valid for small incidence angles ($<30^0$) to small contrasts of the elastic constants across interfaces, Hendrickson et al., (1991), Drufuca and Mazzotti (1995) recommend extension to large incidence angles ($>30^0$) for AVO interpretation and analysis since it reduces ambiguities. The following factors must be considered in the choice of the level of offset sufficiency required for AVO analysis; objective of analysis, cost, geology and tectonics, technical objectives and limitations.

The major concern in AVO processing is to retain true amplitudes of reflectors (Fig. 6). A surface consistent amplitude and phase processing scheme is the necessary signal processing treatment for proper AVO attribute generation from land data. Other basic processing steps are multiple rejection and seismic data migration. Processing techniques such as trace by trace processing (e.g. AGC and true equalization) that are liable to corrupt AVO response temporally and spatially due to the small amplitude analysis used (one trace) should be avoided. CMP gathers resulting from an efficient AVO processing scheme retains any AVO variations due to gas and/or lithology, and minimises processing artifacts which may lead to deteriorations in seismic data quality and subsequent erroneous interpretations. Quality control of the extent to which AVO processed data represents relative amplitudes can be achieved by visual comparison of CMP gathers with synthetic CMP models, and visual inspection of AVO gradient plots

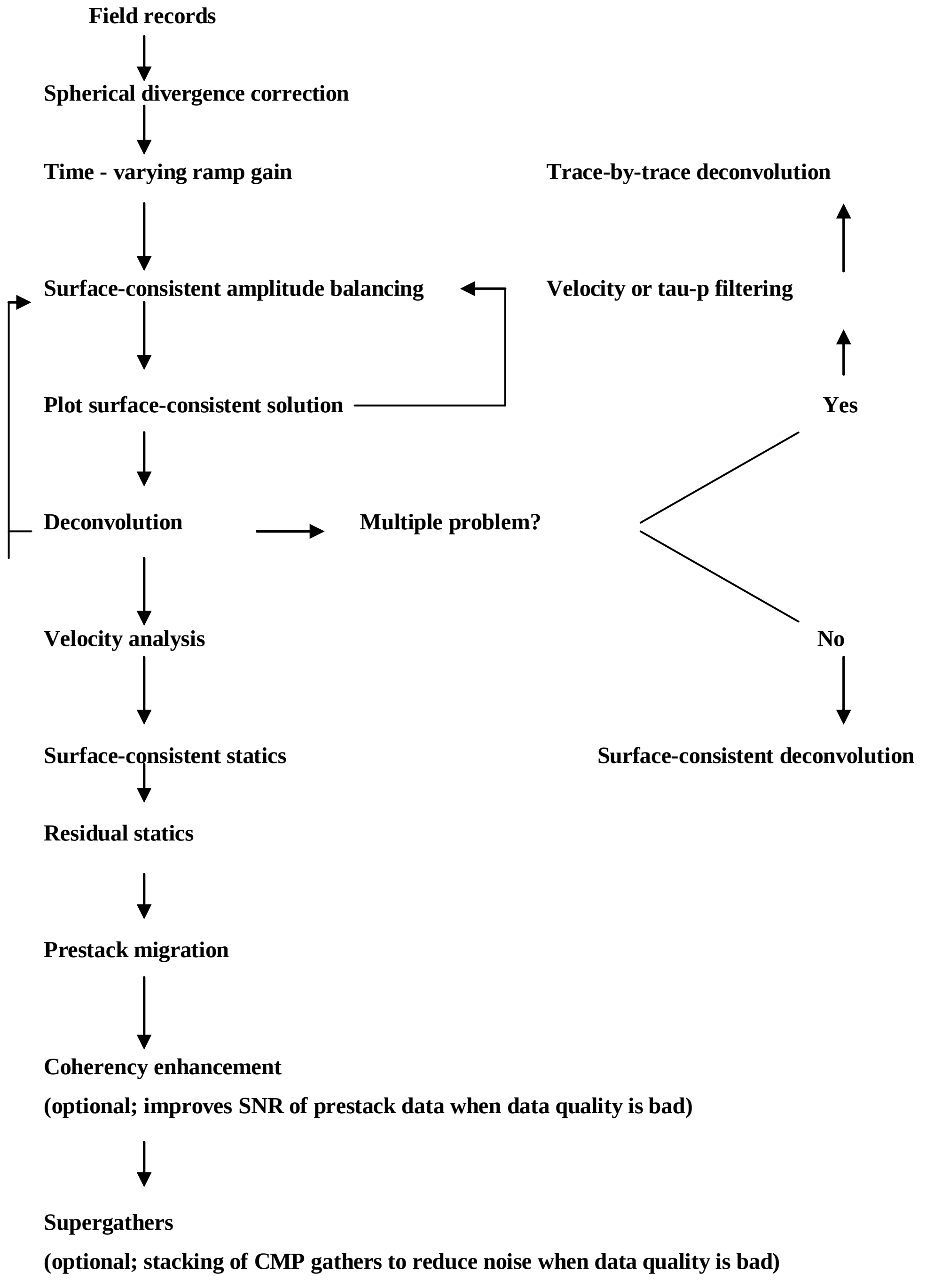


Fig. 6. Flowchart showing the basic processing flow for AVO processing of a typical 3D seismic land data set (Allen and Peddy, 1993).

AVO Interpretation

AVO interpretation involves an attempt to relate deviations from a well defined 'AVO background' trend to gas or lithologic factors. These deviations are termed AVO anomalies. Various indicators of AVO anomalies have been proposed to facilitate the management and interpretation of additional dimensions and great volumes of data inherent in AVO analysis in contrast to conventional seismic interpretation. Castagna and Smith (1994) demonstrate that it is critical to select an AVO indicator that is well-suited to the problem at hand. AVO indicators include, (envFar – envNear)*envFar, P- wave (A), Gradient (B), Product Stack (A*B) or Amplitude vs Gradient Crossplot, (A + B)/2, Angle gathers, Combined/restricted B, Complete angle stacks, and $R_p – R_s$, etc. AVO indicators or attributes highlight amplitude variations with offset. Since simple AVO indicators such as far near stacks can be misleading if used in isolation because of gas independent amplitude variations with offset (AVO), it is often better to use crossplotting techniques (Fig. 7). With AVO anomalies, the seismic interpreter is looking for a specific relationship between the attributes more than he is interested in analysing specific events on individual attribute sections (Canning et al., 2000). Castagna and Swan (1997) propose that the classification of AVO responses should be based on position of the reflection of interest on a B (AVO gradient) versus A (AVO intercept) crossplot (Fig. 7). Brine-saturated sands and shales plot along a clearly defined background trend called the fluid line on such a crossplot. Reflections from the top of sands with pore fluid (such as gas) more compressible than water will plot on a trend shifted down and to the left away from the fluid line.

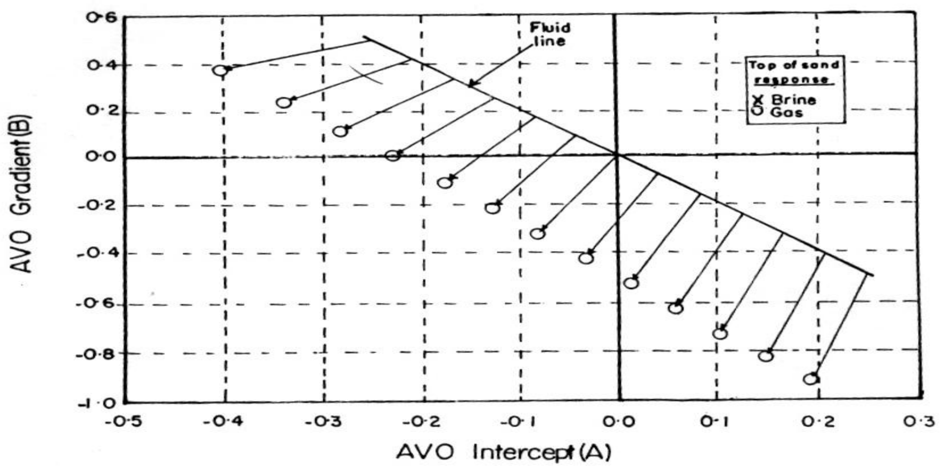


Fig. 7. Expected trend deviation for gas-sands on an B vs A crossplot.

Basically, the following should be observed during AVO interpretation; changes in Poisson's ratio across interfaces, colour variations where colour plots or graphics are applied, the behaviour of AVO indicators, and deviations on a crossplot of AVO intercept (A) and AVO gradient (B) from an expected background response (Fig. 7). The application of these steps facilitates quick and direct discernment of gas influence on seismic data.

(a) Direct hydrocarbon identification based on changes in Poisson's ratio

An increase in Poisson's ratio (Vp/Vs) is indicative of the presence of gas in a reservoir. According to Sickle and Valusek (1990), a small amount of gas in a reservoir causes a sharp decrease in P- wave velocity or a large increase in Poisson's ratio. These changes cause an increase in amplitude with offset (B; Equation 1 and Fig. 4), indicating the presence of gas.

(b) Direct hydrocarbon identification based on colour plots

On processed relative amplitude preserved (RAP) colour plots, \`RED\` colour is indicative of an increase in amplitude or gas, whereas \`BLUE\` colour is indicative of a decrease in amplitude or lithology. In addition, a negative (-ve) AVO response indicates a lithologic event (such as basement, salt, etc.). A positive (+ve) AVO response indicates high amplitudes or gas. It is however important to remember that different classes of gas sands produce different AVO responses (Table 1; Fig. 7).

(c) Direct hydrocarbon identification based on AVO indicators (e.g. R_p-R_s and A*B)

Since a small amount of gas causes a sharp decrease in P- wave velocity, when the value of the reflection coefficient difference of normal incidence P- wave and S- wave (i.e. R_p-R_s) becomes more negative, it is more likely that this is due to the presence of gas. The value of (R_p-R_s) is always negative for reservoir quality gas sands than it is for brine sands. (R_p-R_s) assumes a near-zero value for the case of shale over brine sand. However, the AVO product (A*B) does not have a definite value for gas sands or shale over brine sand. Consequently, it is considered a less better indicator than the (R_p-R_s). It may be positive, negative or near-zero (Table 1). Also gas sand A*B may be more positive, more negative, or about equal to brine sand A*B. The AVO product is strongly positive only when A (intercept) and B (gradient) are both strongly negative. Castagna and Smith (1994) recommend that one should not simply relate A*B to gas content unless it is known a priori that class III gas (Table 1) sand behaviour is expected.

(d) Direct hydrocarbon identification based on deviation from an expected background response:

All AVO analysis should be done in the context of looking for deviations from an expected background response (Castagna and Swan, 1997). Fig. 7 portrays deviations from a background petrophysical trend, resulting from hydrocarbons. Note that the gas sands form a distinct trend away from that of the brine sands. According to Castagna and Swan (1997), the background trend must first be defined either with well control if the seismic data are correctly amplitude calibrated, or the seismic data itself if care is taken to exclude prospective hidden hydrocarbon bearing zones.

AVO LIMITATIONS

Although, AVO analysis has superceded the Bright Spot Technique as a direct gas indicator, it is fraught with limitations such as data quality dependence, insufficient maximum source-receiver offset on seismic data in exploration regions where high-impedance sands predominate, inability to discriminate commercial and non-commercial gas accumulations, poor imaging of reservoirs below the 15 ft lower limit of resolution, non linear reflection amplitude variation with offsets as a result of wave propagation effects such as spreading losses, transmission losses, interbed multiples, etc. AVO analysis is also limited by geologic effects such as terrain/geologic dip and reflector curvature. Better data acquisition, robust AVO processing, with the integration of interpretative aspects such as modeling and inversion may be used to avoid or reduce these AVO limitations.

CONCLUSIONS

Generally, AVO analysis is theoretically more correct and efficient as a DGI than the Bright Spot Technique. Proper data acquisition, selection and pre-stack processing determines its reliability as a DGI. AVO analysis primarily involves an attempt to relate deviations from a well- defined "AVO background " trend to gas or lithologic factors. AVO attribute sections and crossplots facilitate AVO analysis. Although the dependence of AVO behaviour on rock properties and resolution is currently unresolved, in the appropriate geologic terrain AVO analysis can be useful as a DGI. AVO has been shown to be an effective direct gas identification tool in areas such as central Alberta in Canada (Miles et al., 1989), Sacramento basin in California (Sickle and Valusek, 1990), Central Graben in the North Sea (Snyder and Wrolstad, 1992), Eocene Yegua trend of the Gulf Coast (Shirley,1995), offshore central West Greenland (Skaarup et al., 2000), onshore and offshore Niger delta, etc. In these areas, AVO analysis has increased drilling success ratios and overall drilling; with a resultant significant decrease of the cost per well of discovering gas reserves. AVO analysis is also an emerging technology in the appraisal of deep water prospects for probable gas zones in numerous basins.

REFERENCES

Aki, K. I. and Richards, P. G. (1980). *Quantitative seismology*. W. H. Freeman and Co., New York.

Allen, J. L. and Peddy, C. P. (1993). Amplitude variation with offset: Gulf Coast case studies. In: *Geophysical Dev. Series*, Vol. 4(F. K. Levin Ed.),, SEG, Tulsa, Okhlahoma. 126pp.

Bortfield, R. (1961). Approximation to the reflection and transmission coefficients of plane longitudinal and transverse waves. *Geophysical Prospecting*, 9: 485-502.

Canning, A., Litvin, A., and Eastwood, L. (2000). 3D visualisation of AVO anomalies. *First Break*, 18.4: 138-140.

Castagna, J. P. and Smith, S. W. (1994). Comparison of AVO indicators: a modeling study. *Geophysics*, 59(12): 1849-1855.

Castagna, J. P. and Swan, H. W. (1997). Principles of AVO crossplotting. *The Leading Edge*, :337-342.

Dobrin, M. B. and Savit, C. H. (1988). *Introduction to Geophysical Prospecting*. Mcgraw- Hill Book Company, New York, 867pp.

Drufuca, G. and Mazzotti, A. (1995). Ambiguities in AVO inversion of reflections from gas-sand. *Geophysics*, 60: 134-141.

Hendrickson, J. S., Li, S. M., Daste, A. S., and Gunther, G. L. (1991). Evidence of AVO as a direct hydrocarbon indicator and a direct no-hydrocarbon indicator. Shell Geophysical Conference Paper (Unpubl.), 100: 1-24.

Henry, S. (2004). Understanding Seismic Amplitudes. AAPG *Explorer*, 25 (7): 30-31.

Miles, D. R., Canada, T. L., Gassaway, G. S., Bennett, L. E., and Brown, R. A. (1989). Detection of hydrocarbons in reefs using AVO inversion of seismic data: a case history from Alberta, Canada. Soc.Explot. Geophys: 623-634.

Shell Petroleum Development Coorporation (1999). *Shell Nigeria Graduate Training Programme Geophysics Module: Seismic Exploration*. Univation Ltd.

Shirley, K. (1995). Yegua gives AVO a complex test. America Association of Petroleum Geologist (AAPG) *Explorer*: 10-14.

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

Sickle, K. V. and Valusek, J. E. (1990). AVO analysis of 3-D seismic data identifies untested reservoirs in old gas field. The Leading *Edge*:18-22.

Skaarup, N., Chalmers, J. A., and White, D. (2000). An AVO study of a possible new hydrocarbon play, offshore central West Greeenland. America Association of Petroleum Geologist (AAPG) Bulletin, 84 (2): 174-182.

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

Snyder, A. G. and Wrolstad, K. H. (1992). Direct detection using AVO, Central Graben, North Sea. *Geophysics*, 57 (2): 313-325.

Yu, G. (1985). Offset-amplitude variation and controlled amplitude processing. *Geophysics*, 50: 2617-2707.