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DELINEATION OF SHALLOW GAS RESERVOIR USING SEISMIC ATTRIBUTES: IMPLICATION IN RESERVOIR CHARACTERIZATION

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Abstract

In the interpretation of 3D seismic data for hydrocarbon reservoir delineation, low-frequency shadow zones are observed both at shallow depths from reflectors below gas sands, condensates and in much deeper oil reservoirs on seismic reflections. These low-frequency shadow zones are important in reservoir characterization studies, geohazard analysis and drilling of boreholes, because, they depict the likelihood of hydrocarbon reservoir units in the subsurface. In this study, we have used seismic attribute assisted technique and theoretical approach to delineate a low-frequency shadow zone such as shallow gas reservoir (amplitude anomaly) in a 3D seismic data and predict reservoir properties. The result of seismic attributes analysis delineates an amplitude anomaly (bright spot) at an approximate depth of 525ms close to a major fault line. We interpreted the amplitude anomaly (bright spot) as a major hydrocarbon reservoir at shallow depth in the study area, probably due to the presence of biogenic gas pockets that may have migrated to the reservoir zone from the gas formed by thermogenic process at depths well below 1000ms. In addition, thin bed reservoir thickness is estimated at 12.02m which is under seismic resolution. With the available sonic log data of the well passing the reservoir zone, we estimated the porosity of the reservoir zone at 29%. Thus, the reservoir is highly porous and could vary along the reservoir zone. The most negative curvature seismic attribute delineates shallow channel geometry with strong negative anomalies along channel axis in the reservoir zone capable of trapping shallow gas. These strong negative curvature anomalies are interpreted to be sand filled channels that have probably undergone differential compaction.

Keywords: *Delineation, shallow gas, seismic attributes, and reservoir characterization.*

Introduction

Most seismic reflection events recorded in seismic sections are essentially a combination of individual reflections from the various closely spaced reflectors such that they nearly remain constant in acoustic impedance contrast and separation, as such; superimposition of the individual reflections from the closely spaced reflectors may generate a frequency pattern that characterizes the composite function, which more often provides a useful correlation index. However, the composite reflection character gradually changes as the sequence of layers (reservoirs beds) changes in thickness or lithology; as such, changes at pinchouts and edges of hydrocarbon-water interface tend to change instantaneous frequency rapidly (Tanner et al., 1979). Thus, low-frequency shadow zones are often times observed at shallow depths from reflectors below gas sands, condensates and in much deeper oil reservoirs on seismic reflections. To this effect, interpretation of the low-frequency shadow zones in seismic reservoir characterization studies is quiet important, because, they show the likelihood of hydrocarbon reservoir units in the subsurface. This can be achieved by the evaluation of hydrocarbon reservoir properties such as thin bed reservoir thickness, porosity and infill Lithology.

Several published works have thoroughly discussed various aspects of hydrocarbon reservoir properties evaluation. Some of the studies includes, prediction of thin bed thickness using a combination of seismic envelope and instantaneous frequency by Robert and Nogami (1984). Chuang and Lawton (1995) using four wedge models showed that peak frequency does gradually decreases as the thickness of layer or bed increases. Partyka (2001) compared Widess's., (1973) amplitude method of simple measurements of peak to trough travel time as well as discrete Fourier transform components to predict thickness. Mohammed Anees (2013) estimated the porosity and thin bed reservoir thickness of a hydrocarbon reservoir at shallow depth using seismic attributes. Although these studies and others provide very rich literature, much has not been said about shallow gas reservoir units and reservoir infill lithology discrimination based on differential compaction of sediments in this dataset by the petroleum companies who had acquired vast volume of dataset in the study area. Interpretation of the 3D dataset for hydrocarbon exploration and exploitation has been on the much deeper exploration targets. But the delineation of shallow gas reservoir units and evaluation of the reservoir properties is useful in geohazard analysis and drilling of Boreholes, etc in the study location.

In this study, we have used seismic attribute assisted technique to delineate shallow gas reservoir unit along inline 230, predict thin bed reservoir thickness, reservoir porosity and infill Lithology of the reservoir pay zone. We proposed a theoretical approach to thin bed reservoir thickness estimation using peak instantaneous frequency obtained from the amplitude spectrum of the 3D seismic data along in-line 230 by spectral decomposition method. We assume that the thin bed reservoir thickness is less than or approximately equal to the tuning thickness. Porosity prediction of the reservoir pay zone is based on mathematical approach using sonic log data of the available well passing through the reservoir zone. The most positive and most negative seismic curvature attributes were used to discriminate infill lithologies based on differential compaction in the reservoir pay zone.

Instantaneous Frequency Seismic Attribute Review

Analogous to x-ray therapy in medical diagnosis, seismic attributes are referred to as seismic data derivatives. All of the measured quantities obtained from the seismic data. They are classified into physical and geometrical attributes depending on their functional properties in seismic data interpretation. They can be classified qualitatively and quantitatively for the purpose of feature detection and interpretation of physical properties of interest. Thus, instantaneous frequency is an example of physical seismic attribute because it directly relates to wave-propagation, lithology, and other physical parameters of the subsurface rocks and reservoirs. Furthermore, instantaneous frequency can also be referred to as post-stacked attribute since it is computed from the complex (analytical) seismic trace. It is the average frequency of the amplitude spectrum of the seismic wavelet. Among other things, instantaneous frequency is the seismic character indicator. The following are some basic uses of the instantaneous frequency attribute in seismic attribute analysis of seismic data.

- It is used as bed thickness indicator. In principle, high frequencies depict very sharp interfaces or thin shale bedding, whereas, low frequencies indicates the existence of sand rich bedding. Thus, essentially a good tool for sand/shale ratio indication.

- Hydrocarbon indicator by low frequency anomaly. However, this effected is sometimes greatly accentuated the presence of unconsolidated sands primarily due to oil content of the pores.
- To indicate the edges of low impedance thin beds of subsurface rocks or reservoirs.
- Used to detect fracture zones. This appears as low frequency zones.
- Chaotic reflection zone indicator.

Theoretical Background

Mathematically, instantaneous frequency is defined as differentiation of instantaneous phase, expressed as

$$f_i = d\phi / dt \qquad 1$$

Where f_i , ϕ , and t are instantaneous frequency of the complex seismic trace, instantaneous phase of the complex seismic trace and time respectively. Instantaneous frequency can also be defined in terms of average frequency as the conditional average frequency in a specified time range (Robertson and Nogami, 1984; Barnes, 2000; Cohen, 1995), mathematically expressed as:

$$\bar{f}_i = \frac{\int_0^\infty fA(f)dt}{\int_0^\infty A(f)dt} \qquad 2$$

Where f_i, f and $A(f)$ are the instantaneous frequency, frequency of the spectral component and the amplitude spectrum respectively. However, in this paper, we assume discrete frequency spectrum of seismic data to build the mathematical formulation of thin bed thickness prediction using Fourier transform of seismic wavelet e.g. Ricker wavelet and power spectrum principle. Though, field seismic signatures tend to differ considerably from the Ricker wavelet which is a second differential of a Gaussian. But when seismic signatures are approximately close to fractional derivatives of a Gaussian, their corresponding spectra is relatively similar to the Ricker amplitude spectrum. Therefore, the Fourier transform of the zero-phase Ricker wavelet defined in time domain may be expressed as:

$$R(\omega) = \frac{2\omega^2}{\omega^2{}_P\sqrt{\pi}}\exp(-\frac{\omega^2}{\omega_p{}^2}) \qquad 3$$

Where ω and ω_p are angular frequency and peak angular frequency respectively. In terms of instantaneous frequency in Hz, frequency of the spectral component, the Fourier transform of the zero-phase Ricker wavelet can be expressed as:

$$R(f) = \frac{2f^2}{f_p^2\sqrt{\pi}}\exp(-\frac{f^2}{f_p}) \qquad 4$$

Now, following Wang, Y., (2015) expression, we define instantaneous frequency as follows:

$$f_i = \frac{\int_0^\infty f(R^2(f))df}{\int_0^\infty R(f)df} \qquad 5$$

Let $f_i = \frac{D_1}{D_2}$, where D_1 is $\int_0^\infty f(R^2(f))df$ and D_2 is $\int_0^\infty R(f)df$. Now, upon evaluation of these parameters we obtained:

$$D_1 = \int_0^\infty f\left\{\frac{2f^2}{(f^3{}_p)\sqrt{\pi}}\exp(-\frac{f^2}{f_p{}^2})\right\}^2 df = \int_0^\infty (\frac{4f^5}{\pi f_p{}^6})\exp(-\frac{2f^2}{f_p{}^2})df \Rightarrow$$

$$D_1 = \frac{1}{4\pi}\int_0^\infty (\frac{2f^2}{f_p{}^2})^2\exp(-\frac{2f^2}{f_p{}^2})d(\frac{2f^2}{f_p{}^2}) = \frac{1}{4\pi}\int_0^\infty a^2\exp(-a)da \qquad 6$$

Where, $a = \frac{2f^2}{f_p{}^2}$. Therefore, $D_1 = \frac{7}{44} = \frac{1}{2\pi}$

Similarly, $D_2 = \int_0^\infty \frac{2f^2}{(f_p{}^3)\sqrt{\pi}}\exp(-\frac{f^2}{f_p{}^2})df = \int_0^\infty \frac{4f^4}{\pi f_p{}^6}\exp(-\frac{2f^2}{f_p{}^2})df \Rightarrow$

$$D_1 = \frac{1}{\sqrt{2\pi}f_p}\int_0^\infty \frac{4f^4}{f_p{}^4}\exp(-\frac{2f^2}{f_p{}^2})d(\frac{f\sqrt{2}}{f_p}) = \frac{1}{\sqrt{2\pi}f_p}\int_0^\infty z^4\exp(-z^2)dz \qquad 7$$

Where, $z = \frac{(\sqrt{2})f}{f_p}$. Therefore, $D_2 = \frac{3\sqrt{2\pi}}{16\pi f_p}$.

From the above analysis, we deduced the instantaneous frequency as:

$f_i = \frac{D_1}{D_2} = \frac{1}{2\pi}\times\frac{16\pi f_p}{3\sqrt{2\pi}} = \frac{8}{3\sqrt{2\pi}}f_p$ i.e;

$$f_i = \frac{8}{3\sqrt{2\pi}} f_p \qquad 8$$

Materials and Method

In this paper, we analyze a post-stacked time migrated 3-D seismic data acquired from the F3 block in the Dutch sector of the North Sea which was made public through OpendTect share seismic data repository by dGBEarthSciences. OpendTect seismic interpretational software, one unit laptop and desktop with high performance were used. Fig 3.1 below is a 4Dip Steered Median Filtered seismic data along in-line 230 clearly highlighting an amplitude anomaly (bright spot) which could be a shallow gas reservoir close to a major fault line at an approximated depth of 525ms.

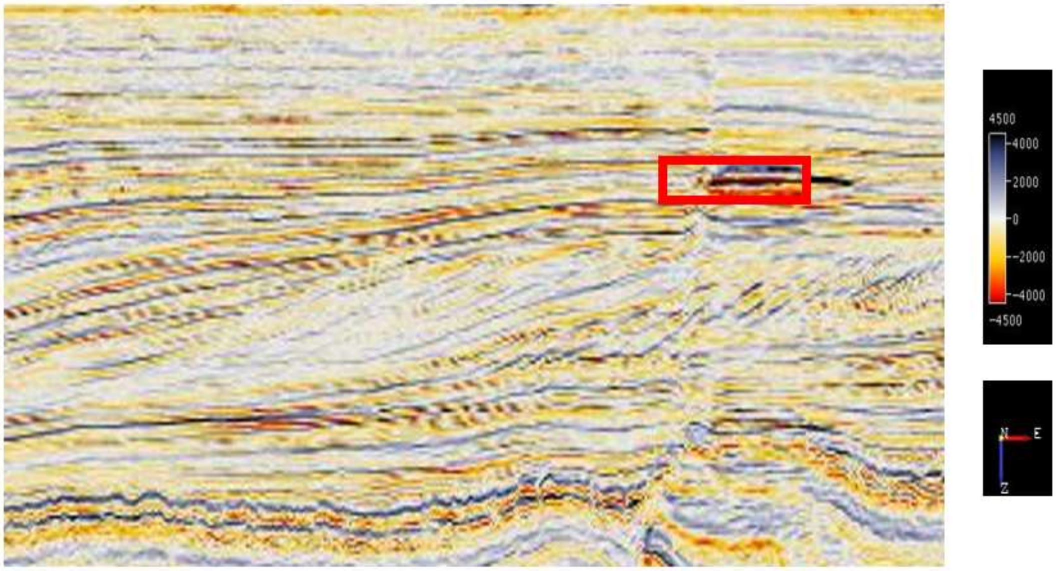
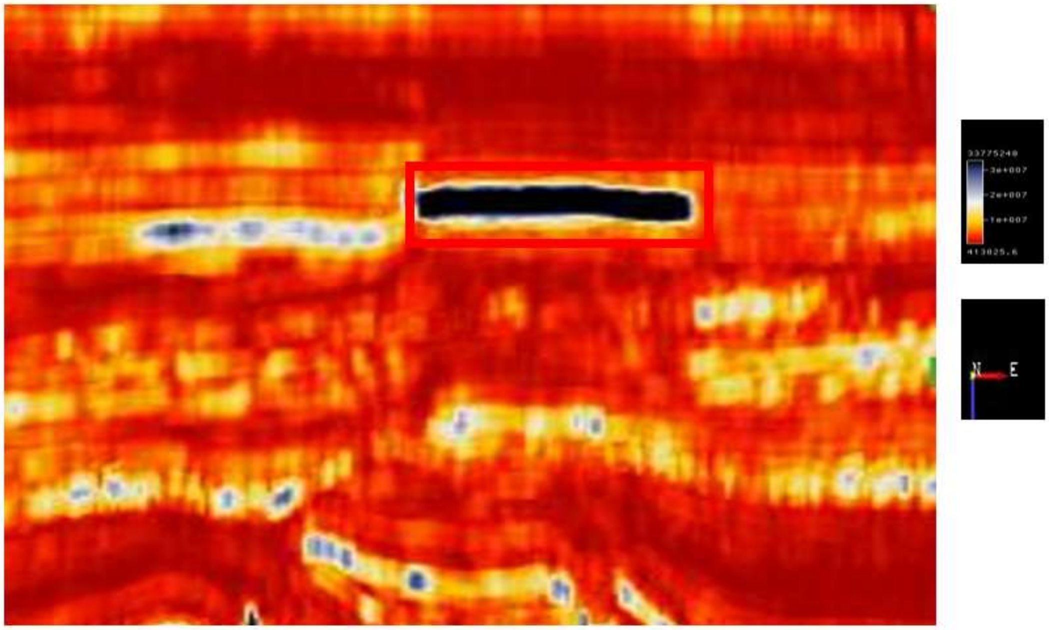


Fig3.1 3D seismic data showing bright spot (red box) along in-line 230 close to a major fault line at an approximate depth of 525ms.

Application of Seismic Attributes to Real Data

To delineate and visualize the presence of bright spot (an amplitude anomaly) as a potential hydrocarbon reservoir in the seismic section along the selected in-line, instantaneous (energy) amplitude was calculated. A bright spot (amplitude anomaly) is clearly detected and visualized at NNE direction close to a major fault line in the seismic section at an approximate depth of 525ms. The name bright spot is a consequence of its bright appearance on the seismic section. In addition, seismic magic attribute was calculated as well to further confirm the presence of direct hydrocarbon indicator as bright spot. Figure 3.2 shows the results of the application of seismic attributes on the seismic section.



(a)

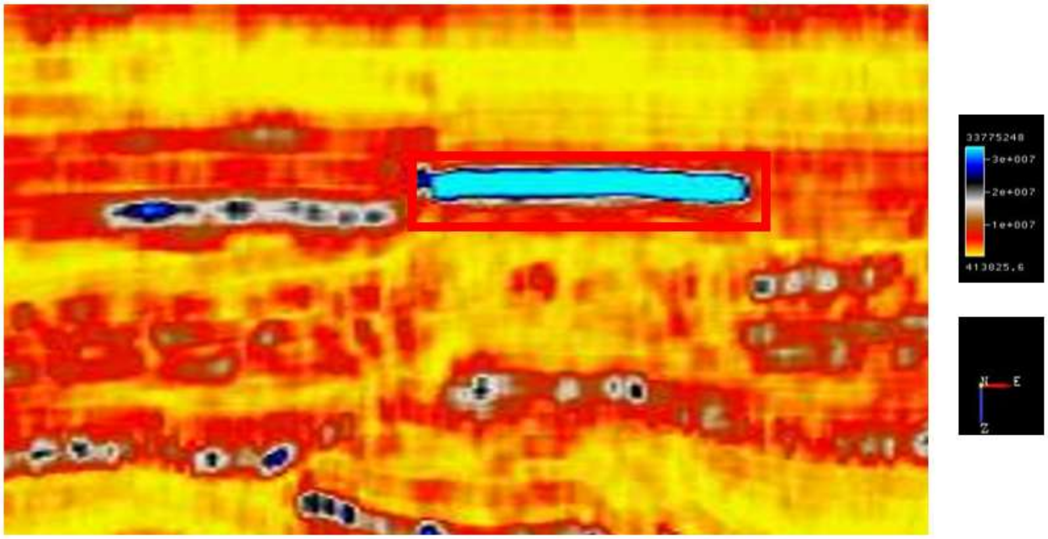


Fig3.2 Bright Spot (red box) visualized and confirmed along inline 230 close to a major fault line at an approximate depth of 525ms using (a) instantaneous (energy) seismic attribute (b) magic seismic attribute.

Thin Bed Reservoir Thickness Prediction.

In order to predict the thin bed thickness of the reservoir, we used the established mathematical formulation relating instantaneous frequency and peak instantaneous frequency e.g. $f_i = \frac{8}{3\sqrt{2\pi}} f_p$. Spectral decomposition analysis is performed along in-line 230 based on Fast Fourier Transform (FFT) where the amplitude spectrum of the seismic section was extracted and the peak instantaneous frequency determined. Figure 2.3 shows the result of amplitude spectrum from the spectral decomposition (FFT) of the 3-D seismic data along in-line 230. From the amplitude spectrum, we observed that, the peak frequency lies around 43Hz. Thus, we deduced the instantaneous frequency as

$$f_i = \frac{8}{3\sqrt{2\pi}} * 43 = 45.75Hz$$

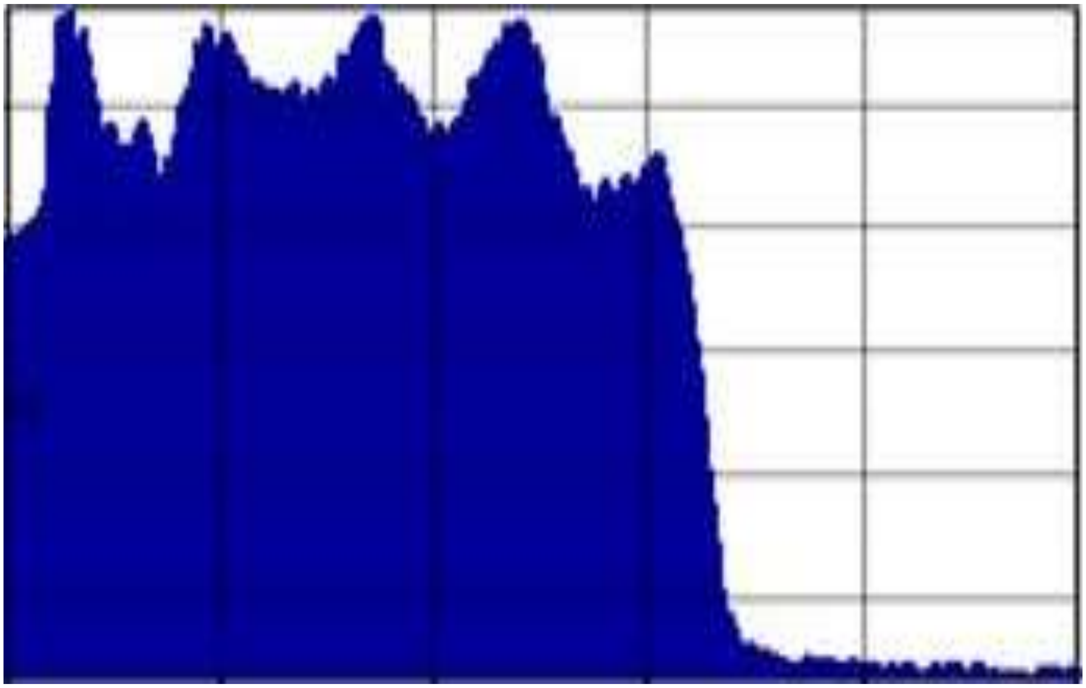


Fig3.3 Amplitude spectrum of inline 230 of the 3-D seismic data

In the absence of drilled well velocity information in the reservoir zone for this study, a P wave velocity of about 2200m/s is assumed. Thus, using the Mathematical relation between frequency (f) and wavelength (λ) expressed as

$f=\dfrac{v}{\lambda}$, thin bed reservoir thickness of the reservoir zone is estimated as

$$T_R=\frac{v}{4f_i}=\frac{2200}{4f_i}=\frac{2200}{4(45.75)}=\frac{2200}{183}=12.02m\,.$$

From the above analysis, the thickness of the reservoir zone is estimated approximately at $12.02ms$. However, this value is slightly less than the reservoir thickness ($T_R=12.22m$) along in-line 228 of same seismic section obtained by Anees (2013) in his paper Seismic Attribute Analysis for Reservoir Characterization. Furthermore, to support the result of the thin bed reservoir thickness from the mathematical computation above, instantaneous frequency attribute was performed on the in-line to x-ray the range of thickness of the reservoir zone. We observed that the reservoir bed thickness in the reservoir zone lies between 11.27m to 269.01m corresponding to the minimum and maximum amplitudes of the instantaneous seismic attribute. Thus, the value of the thin bed reservoir thickness (12.02ms) obtained above lies within the minimum amplitude range which represent the thin bed reservoir thickness and under seismic resolution limit. Figure 3.4 below shows the result of the application of instantaneous frequency attribute.

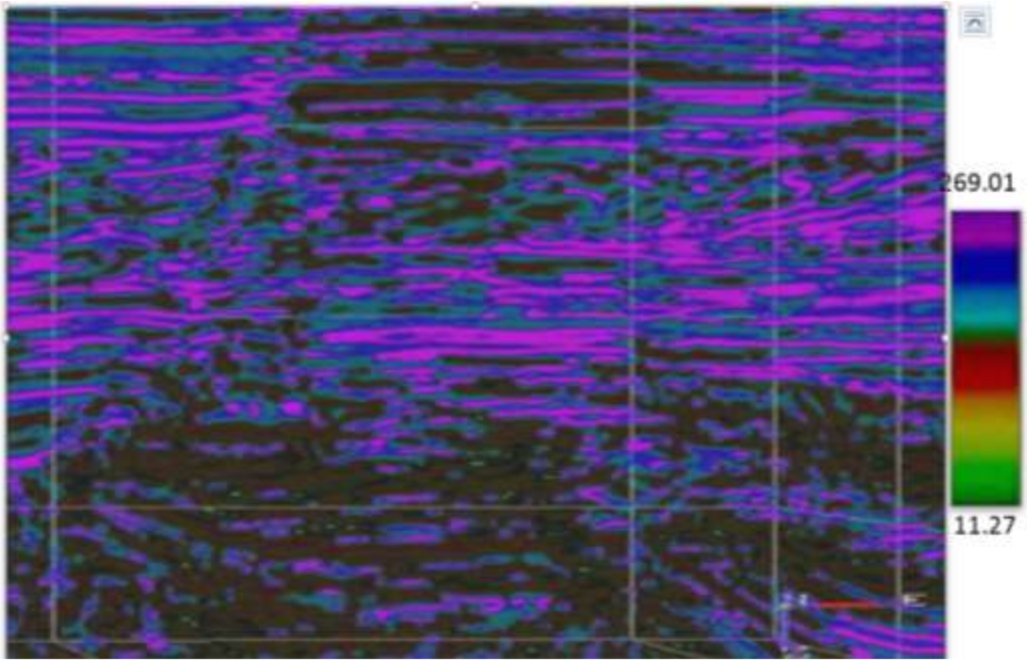
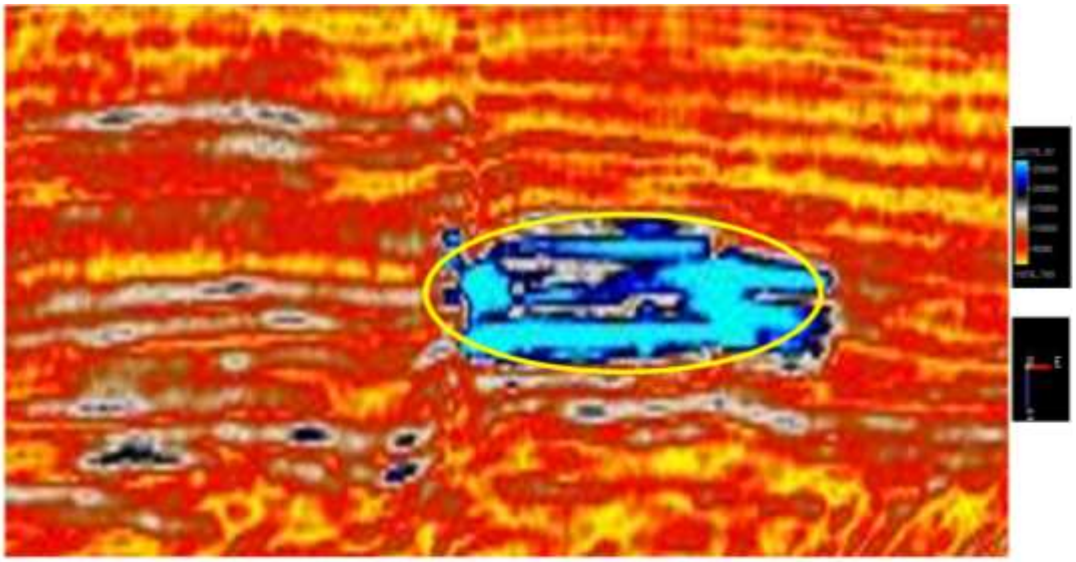


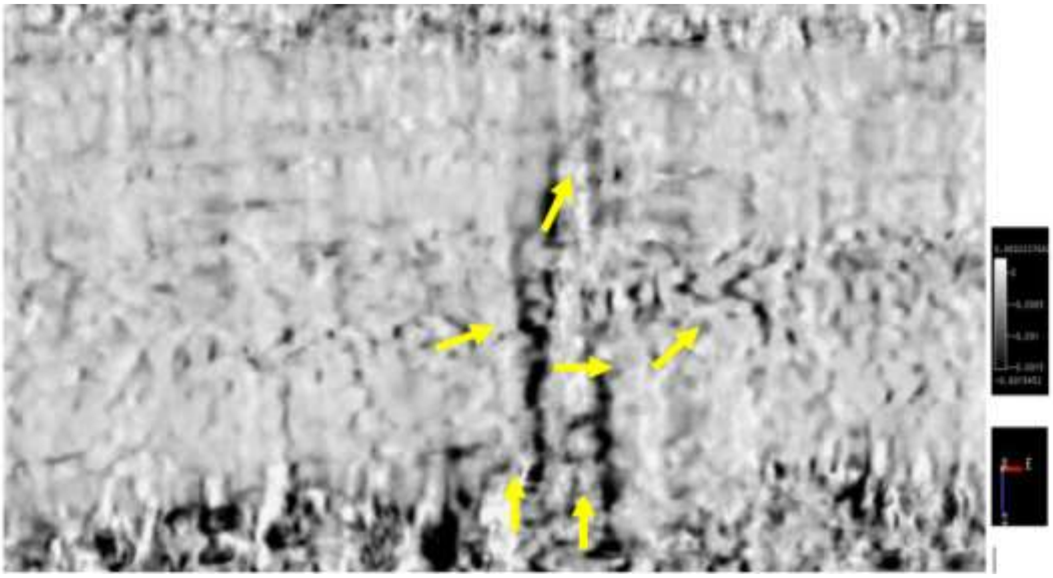
Fig3.4 Result of instantaneous frequency attribute along inline 230 of the 3-D seismic data

Reservoir Infill Lithology Prediction

To predict the reservoir infill lithology, we performed spectral decomposition seismic attribute to delineate the shallow hydrocarbon reservoir unit to evaluate areas of high and low amplitudes within the reservoir unit (Figure 3.5a). The most negative curvature seismic attribute was calculated to delineate the existing shallow channel geometry (yellow arrows) in the reservoir zone. Figure 3.5b shows the results of the application of most negative curvature seismic attribute.



(a)



(b)

Fig3.5 Results of the application of (a) spectral decomposition seismic attribute showing shallow gas reservoir (yellow circle) with areas of high and low amplitudes (b) most negative curvature seismic attribute showing shallow channel geometry (yellow arrows) with strong negative anomaly in the reservoir zone.

Porosity prediction of the reservoir zone

Porosity is a key reservoir property required for seismic reservoir characterization studies. Thus, to estimate the reservoir porosity in this study, we used the available sonic log information of an existing well passing through the reservoir zone (figure3.6). A review of hydrocarbon effects on a formation interval transit time shows that, formation interval transit time increases due to the presence of hydrocarbons. As such, effect of hydrocarbon when not corrected affects the sonic-derived porosity to be very high. To this effect, we used the Hilchie empirical formula for correction of porosity in the computation. Due to non availability of drilled well log information of the reservoir zone we assumed oil to be the hydrocarbon in the reservoir zone, thus, porosity of the reservoir zone is expressed as:

$$\phi = \phi_S * 0.9$$

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Where, ϕ and ϕ_S are the reservoir porosity and sonic-derived porosity. But we know that the sonic derived porosity is expressed as: $\phi_S = \frac{1}{C_P} * (\frac{\delta t_{\log} - \delta t_{ma}}{\delta t_{ft} - \delta t_{ma}})$ (Wyllie equation). Where ϕ_S is sonic derived porosity, δt_{ma} is interval transit time in matrix, $\delta t_{\log}$ is interval transit time in formation, C_P is an empirical compaction factor and δt_{ft} is interval transit time in the fluid in the formation. From Figure 3.6 below, we have that the interval transit time in the formation is approximately $184\mu \sec/ft$, interval transit time in matrix (for shale) is $55.5\mu \sec/ft$ and interval transit time in the fluid (oil is assumed) in the formation is $238\mu \sec/ft$ respectively. Thus, the empirical compaction factor is deduced as: $C_P = \frac{\delta t_{SH} * C}{100}$, Where C is a constant which is usually equation 1 (Hilchie, 1978), and from regional geology δt_{SH} as the interval transit time in a shale adjacent to the formation of interest is approximately $220\mu\sec/ft$. Thus, we have; $C_P = \frac{220*1}{100} = 2.2\mu\sec/ft$

The porosity of the reservoir zone is then deduced as: $\phi = \frac{1}{2.2}*(\frac{184-55.5}{238-55.5})*0.9 = \frac{115.65}{401.5}$

Therefore, reservoir zone porosity is estimated at, $\phi = 0.288 \approx 29\%$.

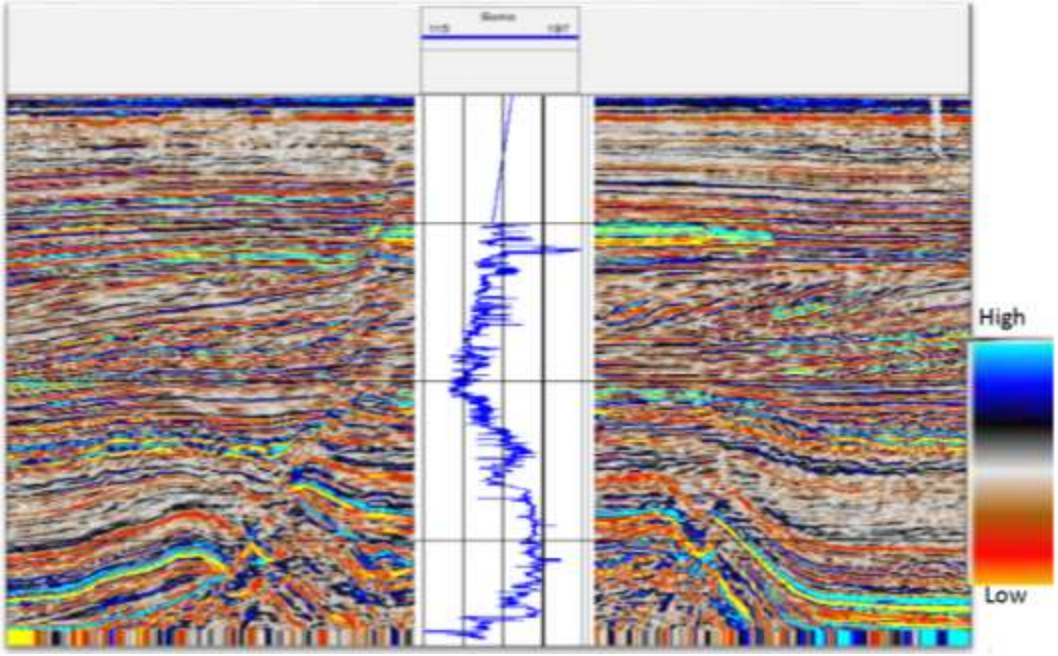

Fig3.6 showing the result of sonic log of an existing well passing through the reservoir zone.

From the available porosity log data of the 3-D seismic data used for this study, porosity of the reservoir zone is estimated to be at 25% - 35%. Thus, the estimated porosity value of the reservoir zone in this study lies within the estimated porosity range.

Results and Discussion

In the interpretation of 3D seismic data for hydrocarbon reservoir delineation, low-frequency shadow zones are observed both at shallow depths from reflectors below gas sands, condensates and in much deeper oil reservoirs on seismic reflections. These low-frequency shadow zones are important in reservoir characterization studies, geohazard analysis and drilling of boreholes, because, they depict the likelihood of hydrocarbon reservoir units in the subsurface. Thus, a seismic reservoir characterization study is to identify the low-frequency shadow zones, delineate hydrocarbon reservoir units, and absolutely determine the reservoir properties distribution. Such reservoir properties include thin bed reservoir thickness, porosity and infill lithology. Among other techniques, seismic attribute analysis is a vital tool employed to achieve this objective. From the results of seismic attributes analysis on the selected inline of the seismic section and analyses of the available well log data for this study, we observed an amplitude anomaly (bright spot) at an approximate depth of 525ms close to a major fault line. We interpreted the amplitude anomaly (bright spot) as a major hydrocarbon reservoir at shallow depth in the study area, probably due to the presence of biogenic gas pockets that may have migrated to the reservoir zone from the gas formed by thermogenic process at depths well below 1000ms. Using a mathematical formulation and amplitude spectrum of the seismic section containing the selected inline, the reservoir bed thickness was estimated at 12.02m which is under seismic resolution.

The seismic spectral decomposition attribute validates the hydrocarbon reservoir and its geometry with areas of high and low amplitudes, and most negative curvature seismic attribute delineates the existing channels geometry which is capable of trapping shallow gas, with a strong negative curvature anomaly along channels axis in the reservoir zone. The strong negative curvature anomaly is interpreted as sand filled channels that have probably undergone more differential compaction. With the available sonic log data of the well passing the reservoir zone, we estimated the porosity of the reservoir zone at 29%. Thus, the reservoir is highly porous and could vary along the reservoir zone.

Conclusion

Delineation of shallow gas reservoirs in 3D seismic data interpretation is important. This is because, it help in geohazard analysis especially in the drilling of boreholes and hydrocarbon reservoir characterization studies. In an attempt to delineate shallow gas reservoir and reservoir characterization, we have used seismic attributes assisted interpretation technique and well log data to predict reservoir properties such as, thin bed reservoir thickness, porosity of the reservoir zone and reservoir infill lithology based on differential compaction of sediments, aimed at characterizing the reservoir. Seismic attribute analysis has proven to be a vital tool for shallow gas reservoir delineation and reservoir properties prediction in this study.

The results show the presence of shallow hydrocarbon reservoir referred to as bright spot, an amplitude anomaly in the NNE direction. The bright spot is indicative of biogenic gas pockets which could be the migrated thermogenic gas formed at deeper depth from the sea surface. The thickness of the reservoir is within seismic resolution and highly porous. In order to determine the infill lithology, we have used seismic spectral decomposition attribute to validate the hydrocarbon reservoir and its geometry, and most negative seismic attribute to delineate the existing channels geometry in the reservoir zone and discriminate between shale versus sand infill lithology based on differential compaction of sediments in channels.

The results show distinct hydrocarbon reservoir geometry and stratigraphic channels geometry with a strong negative anomaly along channels axis. The strong negative curvature anomaly is interpreted as sand filled channels that have probably undergone more differential compaction. However, further reservoir characterization studies such as stochastic inversion and neural network analysis has to be carried out to determine the properties of the reservoir.

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