*IOSR Journal of Applied Physics (IOSR-JAP)*
*e-ISSN: 2278-4861.Volume 9, Issue 5 Ver. II (Sep. - Oct. 2017), PP 18-28*
*www.iosrjournals.org*

# A Case Study on Horizon Based Stratigraphic Channels Delineation Using Fast Fourier Transform and Seismic Attributes: Implications for Reservoir Characterization

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***Abstract:*** *In more recent times, the search for hydrocarbons is geared towards identifying geologically complex and subtle targets such as channels that the traditional seismic sections cannot display since they are very thin (visually subseismic) to their surrounding geometry. These geologically complex and subtle channels filled with porous rock enclosed in a non porous matrix are important stratigraphic events useful in reservoir studies because they constitute hydrocarbon exploration plays; as such, a handful understanding of their stratigraphic geometry and characteristics is an index for seismic reservoir characterization. In this study, seismic spectral decomposition technique such as Fast Fourier Transform (FFT) has been used to decompose a 3D seismic data originally acquired in the F3 block in the Dutch sector in the North Sea from time to frequency domain to delineate stratigraphic channels as possible hydrocarbon traps. A horizon $H_A$ extracted along inline 250 at an approximate depth of 1024ms confirmed using time slice analysis was used for the spectral decomposition process. We also used seismic attributes of semblance and curvature to integrate the results of the Fast Fourier Transform (FFT) and enhance better resolution of channels features. To determine the channels infill lithology, we performed the most negative seismic curvature attribute on the picked horizon to discriminate sand versus shale lithologies on the basis of differential compaction of the channels comparative to its edges. From the results of FFT, we observed the existence of two definite and curvilinear channel features along the NNE-SSW directions which gradually grow thinner and die out northwards. Furthermore, visibly strong negative curvature anomalies are observed along channels axis probably due to differential compaction of the channels infill sediments. We interpreted these negative curvature anomalies to be the softer shale which corresponds to the syncline or saggy in the channels. The resultant ridges observed in the horizon are probably due to stratigraphic channels edges and levees. Thus, this horizon could be a possible prospective hydrocarbon reservoir in the F3 block.*
***Keywords****: Horizon, seismic attributes, stratigraphic channels, spectral decomposition, and reservoir characterization.*

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Date of Submission: 13-08-2017 Date of acceptance: 18-08-2017

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## I. Introduction

In the past decades, interpretation of traditional seismic data for the characterization of hydrocarbon reservoirs and the eventual exploration and production of hydrocarbon in oil and gas fields was based on surface signs visible in the seismic data often referred to as structural reservoirs. However, these easy to find structural reservoirs are almost unavailable because of continues exploitations. In recent times, seismic exploration for hydrocarbon reservoirs delineation is now based on the search for the very subtle, geologically complex stratigraphic traps such as channel, incised valley-filled sands etc, in the seismic sections. These stratigraphic traps are generally sub-seismic (very thin to their surrounding geometry) such that they are nearly invisible in the traditional seismic data. Thus, it is imperative to decompose the seismic data to reveal these subtle subsurface geological features e.g. channels confined to a given stratigraphic horizon. To achieve this objective in seismic data interpretation, the novel spectral decomposition (SD) methods have to be employed. The primary reason is that, the seismic signal is non-stationary in nature, its frequency content vary with time (and depth) since the earth is a non-stationary medium. As such, spectral decomposition of seismic data is necessary. It is aimed at characterizing the time-dependent frequency response of subsurface rocks and reservoirs since different geological events respond to different frequencies. Spectral decomposition effectively unravels the seismic (data) signal into its constituent frequencies and allows the interpreter to aptly visualize the amplitude and phase tuned to specific wavelets analogous to the turning of a radio-set to be at resonance with a particular radio-station of its operational frequency and wavelength.

To compliment the results obtained from the spectral decomposition of 3-D seismic data, seismic attribute analysis has to be performed on the seismic data under suitable conditions. This would also help image

the existing subtle subsurface geological features such as stratigraphic channels boundaries and detect channel edges easily in the 3-D seismic data. Nonetheless, seismic attributes cannot detect channel's thickness, especially when channels are very subtle and thin i.e. below a quarter (1/4) wavelength. Under such condition their waveform becomes constant; as a result, seismic attributes such as coherence attributes cannot image the stratigraphic channels since their measurement is a function of waveform shape (Chopra and Marfurt, 2007). Therefore, seismic attributes are derivatives of seismic data (all the information obtained from the seismic data) for the purpose of feature detection and predict physical properties of interest. There are several seismic attributes with different characteristic property used for seismic feature detection and interpretation (quantitatively and qualitatively). Their principle of operation is similar to X-ray therapy in medical diagnosis.
The main objective of this study is to delineate the subtle stratigraphic traps e.g. channels in the horizon of interest, to show the usefulness of fast Fourier transform technique and seismic attribute analysis in reservoir studies, and to help increase the chances of success and development of new prospect areas in the study location. Thus, spectral decomposition method e.g. Fast Fourier Transform (FFT) and seismic attributes such as Semblance and Curvature attributes were used to delineate stratigraphic traps such as channels confined in a given stratigraphic horizon. The most negative seismic curvature attributes was used to discriminate the channels infill lithology with implications for reservoir characterization in the study area.

## II. Spectral Decomposition Methods

### 2.1. Discrete Fourier Transform (DFT)

Discrete Fourier Transform (DFT) is one of oldest methods of frequency decomposition in signal transform. It is used to extract the local spectrum (frequency) of a signal by calculating the relative intensity of each frequency component of the whole signal. However, a non-stationary signal when transformed into the frequency domain using the Fourier transform, gives the overall frequency behavior; such a transformation is inadequate for analyzing a non-stationary signal such as a seismic signal, whose frequency content varies with time. Therefore, Discrete Fourier Transform (DFT) lacks the provision for any useful information about the changes in the frequency contents with time. As such, Discrete Fourier Transform (DFT) method is inappropriate for seismic signal (non-stationary) transform analysis, and therefore cannot determine frequency content changes with time. Mathematically, The Fourier transform $F(\omega)$ of a time-domain seismogram f(t) is the inner product of the signal with the basis function $e^{i\omega t}$, i.e.

$$F(\omega) = [f(t), e^{i\omega t}]$$

$$= \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \qquad (1)$$

Where t is time and $\omega$ is the angular frequency which is related to the linear temporal frequency f. Suppose that the seismic signal is considered as a complex trace according to Tanner et al. (1997), the signal consists of real and imaginary parts as expressed as follows:

$$f(\omega) = f_r(\omega) + i f_i(\omega) \qquad (2)$$

Where the amplitude spectrum of the signal is obtained as

$$A(\omega) = \left[ f_r^2(\omega) + f_i^2(\omega) \right]^{\frac{1}{2}} \qquad (3)$$

And the phase spectrum of the signal obtained $\phi(\omega) = \tan^{-1}\left[\frac{f_i(\omega)}{f_r(\omega)}\right]$ (4)

Furthermore, other than the inadequacy of the Discrete Fourier Transform (DFT) method, one major limitation of this method is spectral smearing. Secondly, it gives scalar attributes and an average representation of the frequency behavior in the entire seismogram without basic information about the local concentrations of energy. This can be greatly improved by the application of Short Time Fourier Transform (STFT).

### 2.2 Short Time Fourier Transform (STFT)

The Short-Time Fourier Transform (STFT) is a signal analysis with a fixed resolution. It is also known as Windowed Fourier Transform. Short-Time Fourier Transform (STFT) method for signal analysis was developed because of the need for spectral representation of a signal that incorporates the time-varying properties of a non-stationary signal. Practically, Short-Time Fourier Transform (STFT) maps a seismogram into a 2-D frequency-time (F-T) plane. Assuming, the seismic signal (time-domain seismogram) $f(t)$ is defined to be stationary as seen through a predetermined or fixed window length $\phi(t)$, centered at a given location expressed as $\tau$ , and then we define STFT as the inner product of the signal $f(t)$ with a time-shifted window function $\phi(t)$ . Mathematically, it can be expressed as

$$STFT(\omega,\tau) = \left\{ f(t), \phi(t-\tau)e^{i\omega t} \right\}$$

$$= \int_{-\infty}^{\infty} f(t)\bar{\phi}(t-\tau)e^{-i\omega t}dt \qquad (5)$$

Where the window function $\phi$ is centered at time $t = \tau$, with $\tau$ being the translation parameter, $\bar{\phi}$ is the complex conjugate of $\phi$ and $e^{-i\omega t}$ is the Fourier kernel. The Short-Time Fourier Transform (STFT) depend largely on the choice of window g(t) (A. Chakraborty et al. 1995). The following are common limitations associated with the Short-Time Fourier Transform (STFT) e.g. limitation in time-frequency resolution, and decrease in resolution capability. This is probably due to the use of finite- length time domain moving windows over which the 1-D Fourier transforms are performed. In practical application, the finite-length time domain windows move along the seismogram (seismic signal) with an infinitesimal time increment that is much smaller than the width of the windows. This result into the creation of the F-T transform by finer sampling along the time axis. The STFT can be improved by Fast Fourier Transform (FFT) and Wavelet Transform.

**2.3 Hilbert Transform (HT)**

M.T. Tanner et al. (1979) introduced complex trace analysis of an analytic signal that facilitated the separation of instantaneous amplitude and phase information into distinct displays, and computation of instantaneous frequency. The measured seismic signal was considered as the real component of an analytic signal. Practically, Hilbert Transform (HT) is a filter operation that permits the passage of the amplitude of the spectral components without any alteration but significantly alters the phases of the spectral components by $\pi/2$ (ninety degrees). Thus, a complex seismic signal $h(t)$ can be formed using Hilbert Transform as: $h(t) = H_r(t) + jH_i(t)$, where $H_i(t)$ is the Hilbert Transform of $H_r(t)$ . The instantaneous amplitude (envelope or reflection strength), instantaneous phase and instantaneous frequency are obtained as follows:

$$A(t) = \left[H_r^2(t) + H_i^2(t)\right]^{\frac{1}{2}} \qquad (6)$$

$$\phi(t) = \tan^{-1}\left[\frac{H_i}{H_r}\right] \qquad (7)$$

$$\frac{d\phi(t)}{dt} = 2\pi f \qquad (8)$$

These attributes are similar to the Fourier attributes. Furthermore, the Hilbert Transform has the limitation of computational truncation due to its sensitivity to noise. This can be improved by the application of Generalized Hilbert Transform (GHT).

**2.4 Fast Fourier Transform (FFT)**

The Fast Fourier Transform (FFT) is a classical approach used in extracting and evaluating the frequency spectrum of a seismic data. It has the capability in detecting reservoir stratigraphy characteristics such as reef (carbonate reservoir), channel body (Saadati Nejad et al., 2011) and other stratigraphic features (Partyka et al., 1999). It uses the windowing concept of a seismic data as a function of its temporal resolution. Therefore, choosing appropriate time gate or window length in this method helps to reveal more geological features in the seismic data. That is, selecting an optimal window length is important as it is convolved with a Gaussian window. In this way, the Fourier Transform of the window can be determined. It is important to know that by preselecting a temporal window length or choosing a predetermined time gate, the time frequency resolution becomes fixed over the entire time-frequency space. Thus resolution in seismic data analysis becomes dependent on user-specified window length.

Furthermore, the theoretical basis of Fast Fourier Transform (FFT) is essentially build from the Short-Time Fourier Transform (STFT) in which a time-frequency is produced by taking the Fourier Transform (FT) over a short time window. The basic idea is to divide the non-stationary signal into small segments (which are considered stationary parts) and calculate the Fourier Transform for each segment. Mathematically, STFT is the inner product of signal $u(t)$ and a time shifted window $g(t-\tau)$ in time $\tau$ and the frequency ω as shown in Eq (1):

$$STFT_{(\tau,\omega)} = \left[ u(t)\, g(t-\tau) e^{-i\omega t} \right]$$
$$= \int_{-\infty}^{+\infty} u(t)\, \bar{g}(t-\tau) e^{-i\omega t} dt \qquad (12)$$

Where $\bar{g}(t-\tau)$ is the complex conjugate of $g(t-\tau)$ .

**2.5 Location Of Study**

The study area is the Dutch Offshore F3 block, in the Dutch sector of the North Sea. It is located on the top of the Dutch central Graben as one of the main constituents of the Kimmerian Rift Basins at Dutch Northern offshore and as a part of the structural element of the Mesozoic Southern North Sea Rift system (de Jager, 2007). It covers a total area of approximately 386.929sqkm. The study area lies on latitude N45$^{0}$52$^{1}$ and longitude E4$^{0}$48$^{1}$ in the Northern North Sea. Figure 1 show below shows the location of the study area.

Figure 1. Showing the map of the study area.

**2.6 Geological Setting**

Geologically, the F3 block is primarily situated on the top of the Dutch central Graben (shelf of the North Sea) as one of the major Kimmerian rift basins in the Dutch northern offshore and a part of the structural element of the Mesozoic Southern North Sea rift System (de Jager, 2007). It is essentially characterized by great horizontal and vertical variability. According to Patrycja Michalowicz, (2016), three generational faults system is notable in the F3 block. The first generations are known to be reversing, oblique-slip, sinistral faults with orientation SSW-NNE. The second generation are normal, oblique-slip, dextral faults with orientation W-E, and the third generation are faults disturbed by Permian halokinesis which are genetically linked with faults from first and second generation. The Permian diapirs were probably formed from pre-existing faults, which together with the movement of salt were transformed and expanded. Furthermore, the petroleum system of the study area is built by different proven hydrocarbon plays, including Paleogene, Neogene and Quaternary play (de Jager and Geluk, 2007).

## III. Materials And Method

**3.1 Data Set**

The seismic data used in this study is the post-stacked time migrated, 3-D seismic data set of the Dutch Offshore F3 block, originally acquired by dGB EarthSciences and was made available through OpendTect share seismic data repository for the purpose of training and research in geosciences. It covers an approximate area of 386.929sqkm, consists of 646 in-lines and 947 cross-lines, a line spacing of 25m for both in-lines and cross-lines with 1ms sample rate. The 3-D dataset has CC-BY-SA3.0 license held by dGB Earth Sciences. The original data set is noisy; as such a 4Dip-Steered Median Filter was used to filter off the noise. Figure2 show the 4Dip-Steered Median Filtered 3-D seismic data along in-line 250 (at an approximate depth of 530ms).

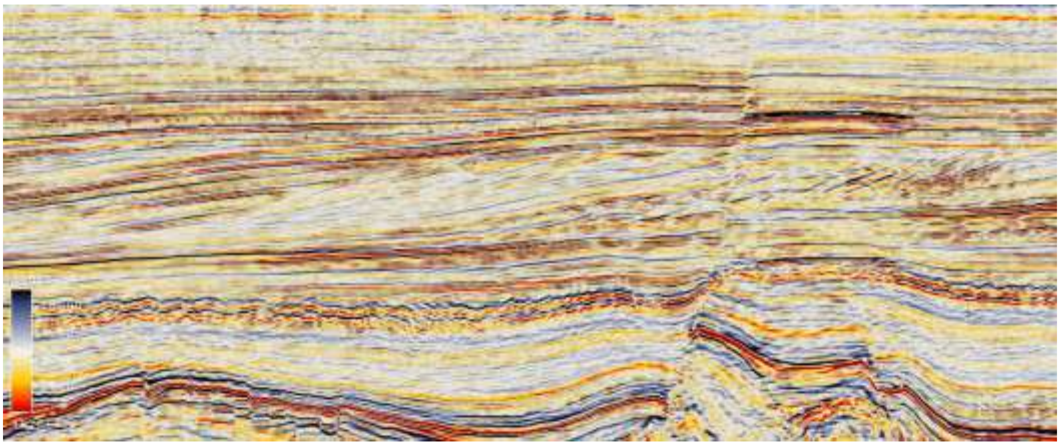
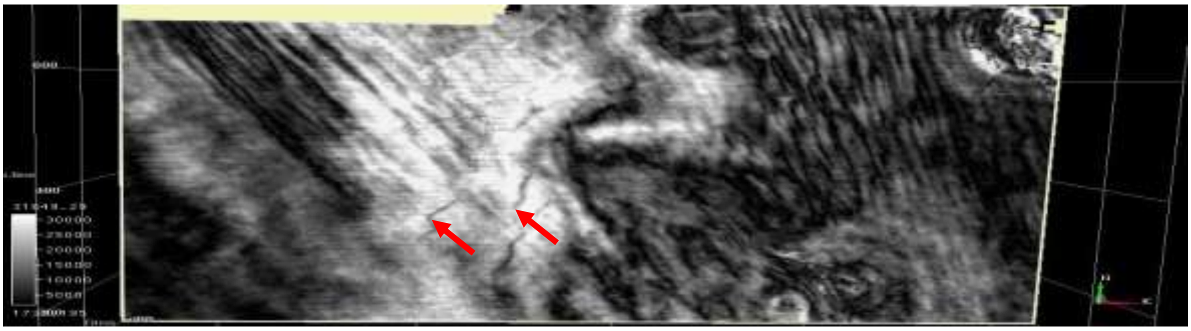


**Figure2** 4Dip –Steered Median Filtered 3-D seismic data along in-line 250 (at an approx. depth of 530ms) showing an amplitude anomaly in black at the top right corner.

**3.2 Methodology**

The principal focus in this study is to delineate stratigraphic channels confined to a given stratigraphic horizon in the 3-D seismic data using Fast Fourier Transform (FFT) as spectral decomposition method and seismic attribute analysis aimed at characterizing the reservoir. The open source seismic interpretation soft ware called OpendTect was used. The procedure we adopted is based on the extraction of horizon of interest from the 3-D seismic (volume) data along in-line 250 at a depth range confirmed using time-slice analysis. On this premise, time-slices as shown in figure3, were extracted at a frequency of 24Hz and step 16 to demarcate the depth range (1000ms to 1048ms) were the horizon of interest lies along the said in-line in the 3-D seismic data. From the time-slice analysis, we observed that, below the depth of 1000ms and above the depth of 1048ms, times-slices did not capture any recognizable stratigraphic channels like features, as such, the horizon of interest was estimated to lie between the of depths of 1000ms and 1048ms, typically at an approximate temporal depth of 1024ms along in-line 250 in the 3-D seismic data as in figure 4. Consequently, the horizon was extracted and then SD method such as Fast Fourier Transform (FFT) and seismic attributes e.g. Semblance and curvature were calculated on the horizon of interest. First, FFT as spectral decomposition method was calculated on the horizon of interest as iso-frequency seismic sections in frequencies of 24Hz, 50Hz and 64Hz respectively using a pre-selected time intervals (temporal windows) of 14ms, 28ms, 56ms and the results were based on a temporal depth of 1024ms. Figures 5 to 7 shows the results of FFT application on the horizon of interest.



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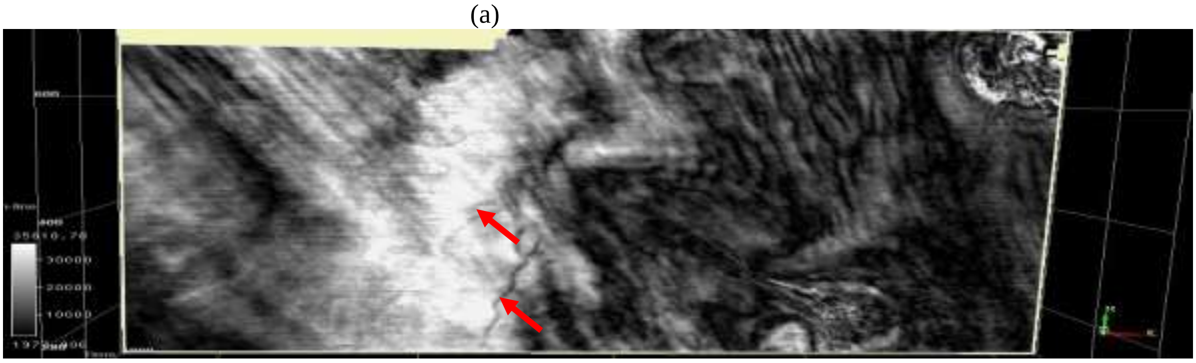

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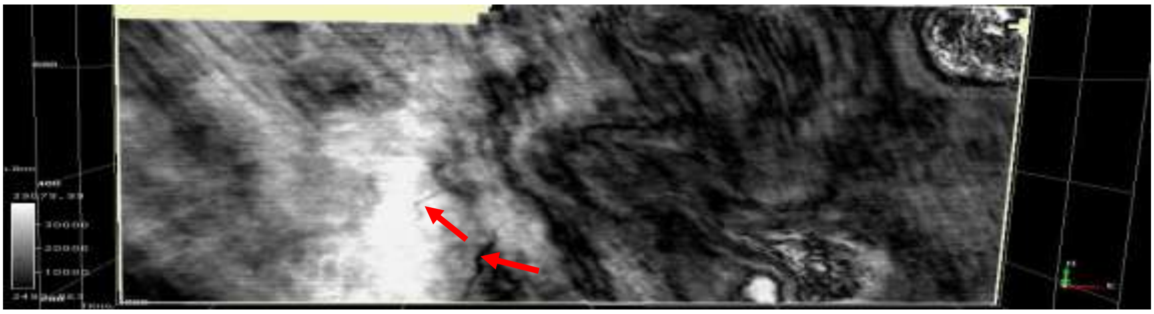

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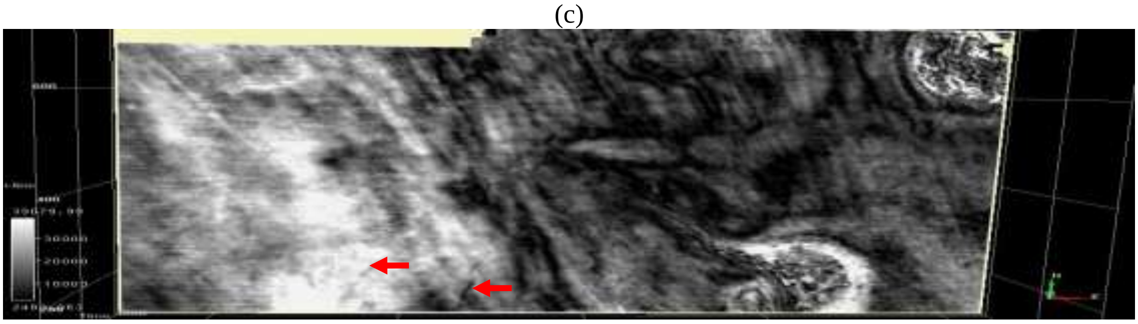


(d)

Figure3. Shows time-slices at frequency 24Hz delineating stratigraphic channels (red arrows) at a depth range of 1000ms to 1048ms were the horizon of interest lies. (a) time-slice at depth of 1000ms. (b) time-slice at depth of 1016ms. (c) time-slice at depth of 1032ms and (d) time-slice at depth of 1048ms.

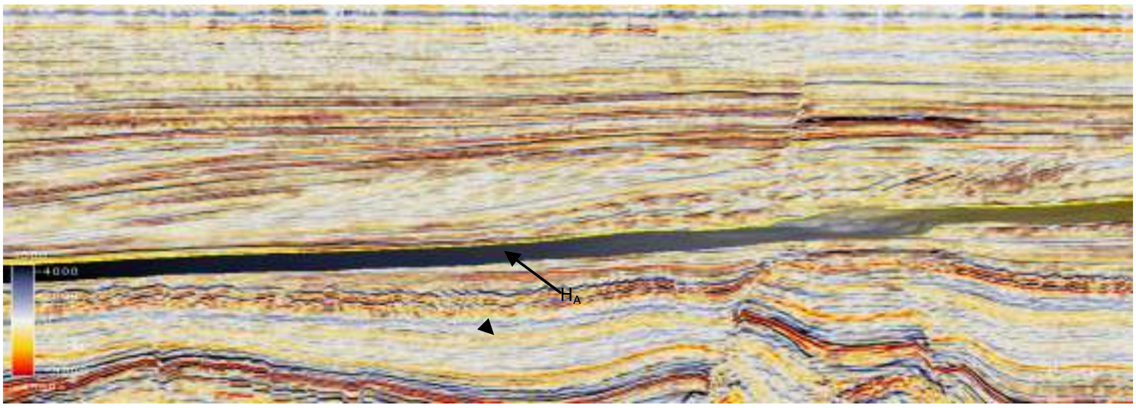
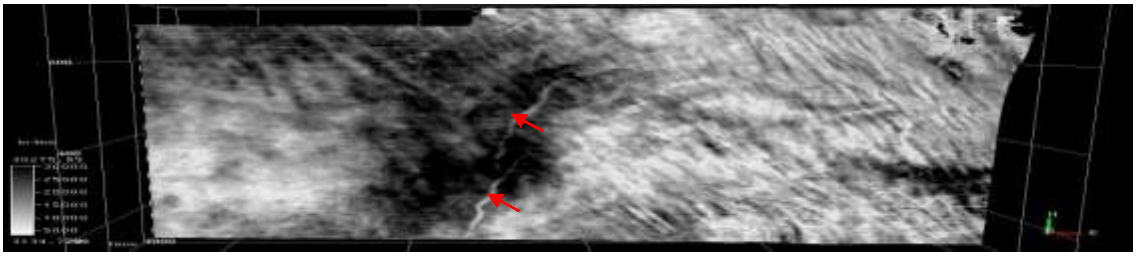


Figure4. Shows the horizon of interest (black arrow) at an approximate depth of 1024ms along in-line 250 of the 3-D seismic data.



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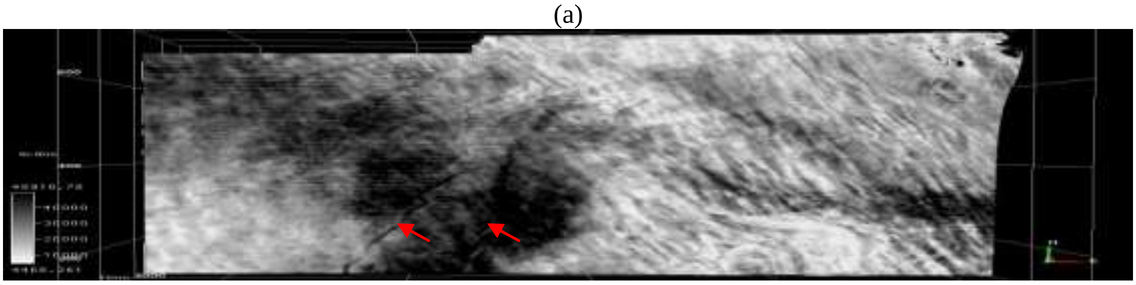

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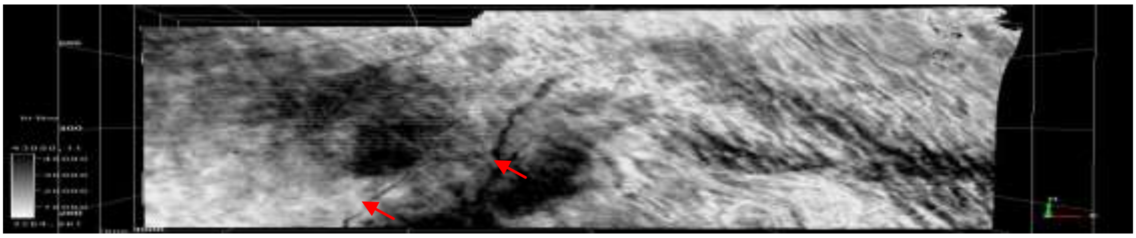
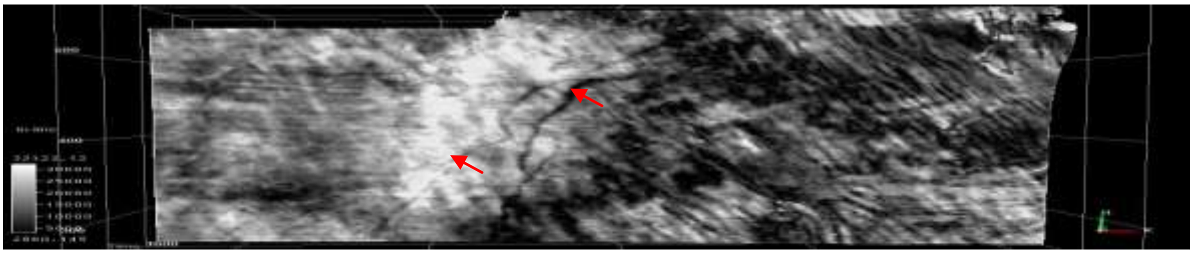


(c)

Figure 5. Illustrates FFT results of iso-frequency of 24Hz, 50Hz and 64Hz at time interval of 14ms and approx. depth of 1024ms. (a) 24Hz freq (b) 50Hz freq. and (c) 64Hz freq.



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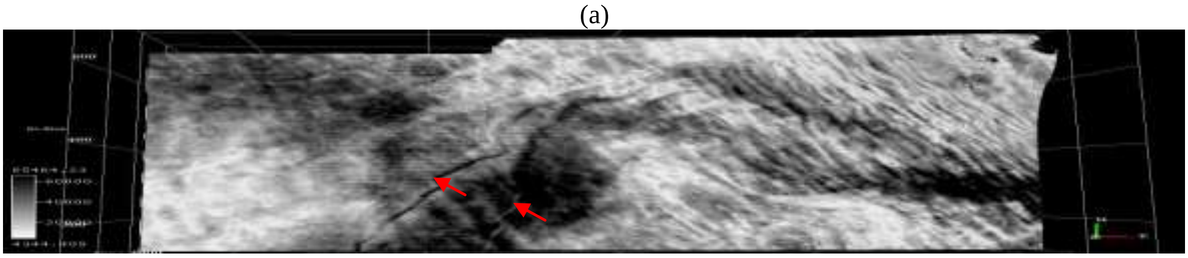

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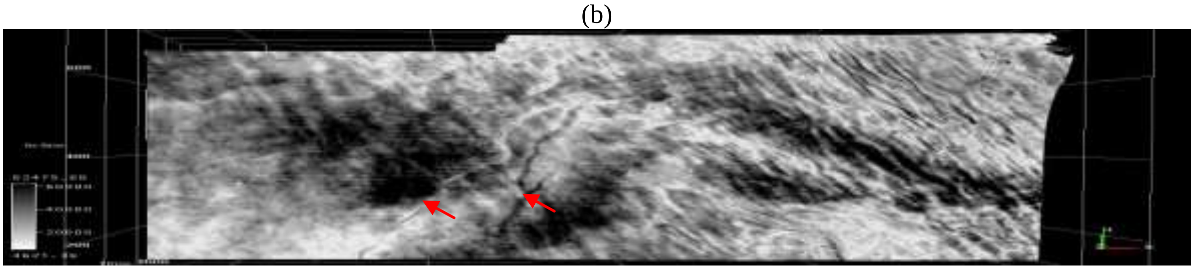
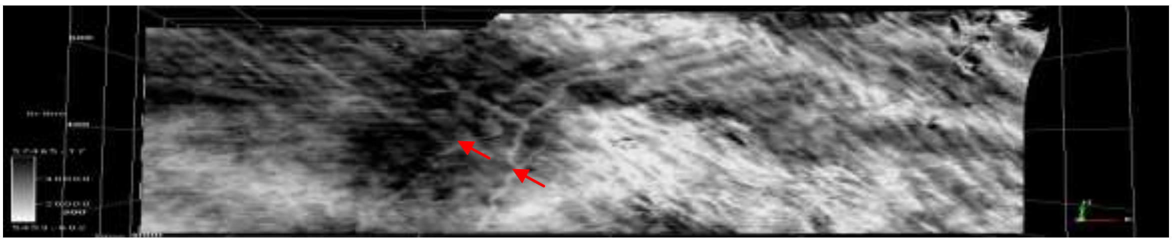


(c)

Figure 6. Illustrates iso-frequency of 24Hz, 50Hz and 64Hz at time interval of 28ms and approx. temporal depth of 1024ms. (a) 24Hz freq (b) 50Hz freq (c) 64Hz freq.



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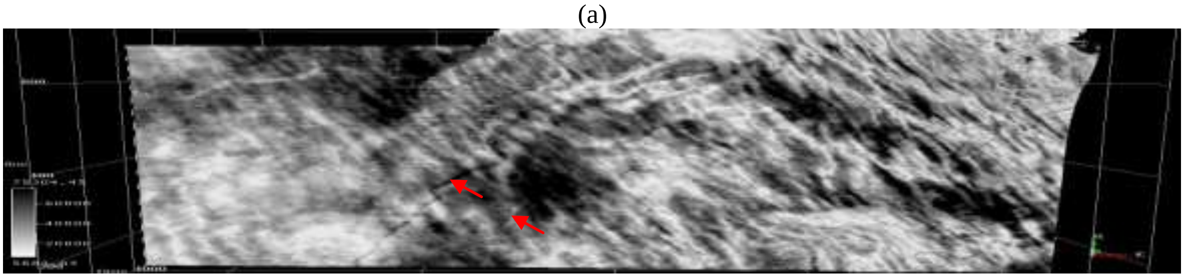

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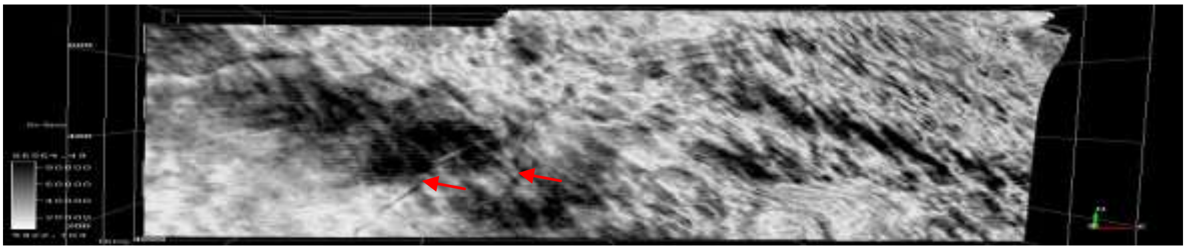

(c)

Figure 7. Illustrates FFT results of iso-frequency of 24Hz, 50Hz and 64Hz at time interval of 56ms and approx. temporal depth of 1024ms. (a) 24Hz freq (b) 50Hz freq (c) 64Hz freq.

Secondly, to compliment the results of the application of the spectral decomposition method, seismic attribute analysis was also calculated on the horizon of interest. Specifically, semblance and curvature attributes combined with grey-scales attribute were calculated on the horizon of interest to further delineate the presence of stratigraphic channels bodies beneath the selected horizon within the approximate depth range. The application of gray-scales attribute help to increase the resolution of the stratigraphic channels in the selected horizon, thus, clearly highlights the existing channel bodies. Figure 8 and figure 9 respectively, shows the result of seismic attributes analysis on the horizon of interest. Furthermore, to determine the channels in-fillings such as sand versus shale lithologies, most negative seismic curvature attributes was calculated on the horizon of interest (figure 10). After the entire procedure, we studied carefully the various spectral decomposition responses for the different stratigraphic channel of the iso-frequencies and the channels infill lithology. Without any loss of generality, each frequency component was expected to buffer the desired understanding and help in the interpretation of the subtle stratigraphic channel details for better hydrocarbon reservoir characterization.

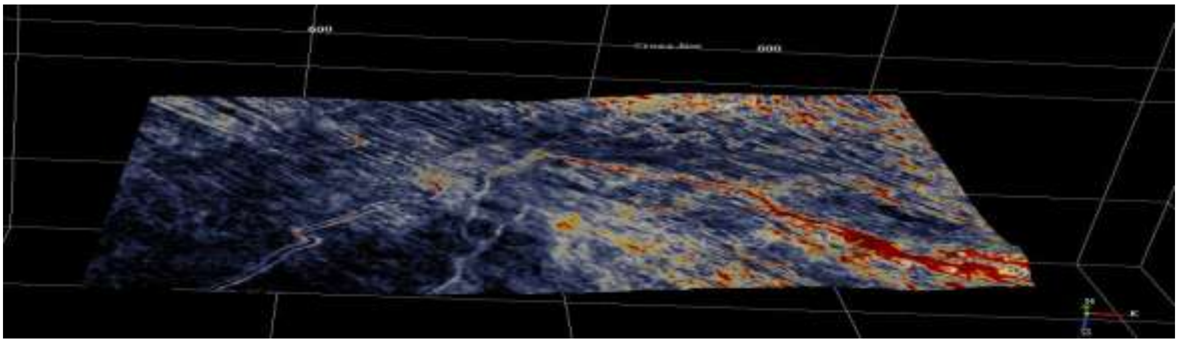

Figure 8. Shows result of seismic semblance attribute calculation on the horizon of interest depicting the stratigraphic channel structures.

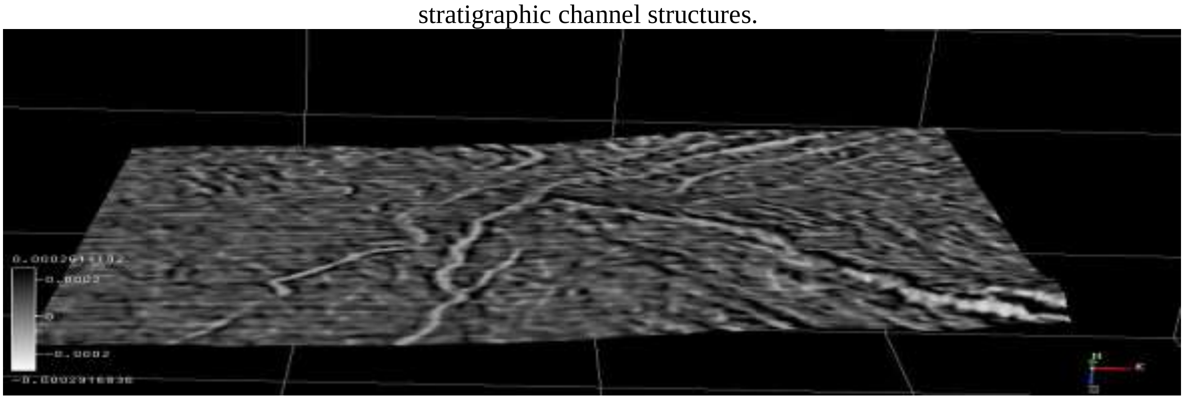

Figure 9. Shows result of seismic curvature attribute calculation on the horizon of interest depicting the existing stratigraphic channel structures.

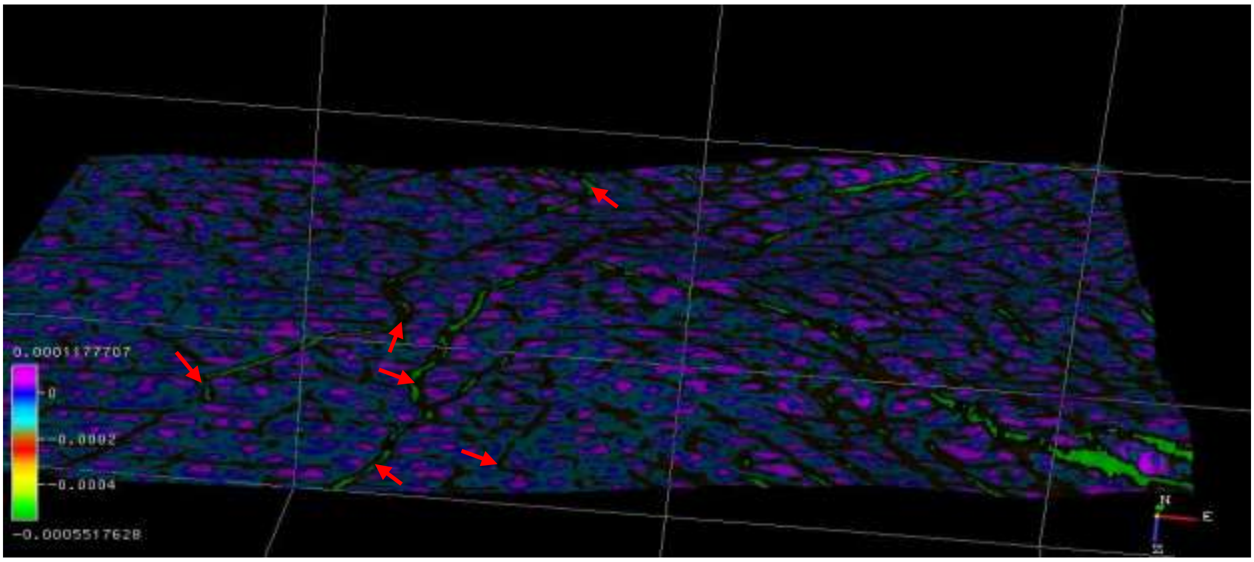


Figure 10. Most negative seismic attribute showing syncline or saggy (red arrows) in channels which depicts negative curvature anomaly.

## IV. Results And Discussion

**4.1 FFT Results.**

Beginning with Fast Fourier Transform (FFT) analysis, seismic time slices were taking across the horizon of interest were the stratigraphic channels like features are targeted for this study. The time slices covering a depth range of 1000ms to 1048ms in the interpreted horizon along in-line 250 shows that channel's seismic expressions are obviously visible at an approximate depth of 1024ms as in figure 3. Analyzing the results of the iso-frequency images in figures 5 to 7 obtained from the Fast Fourier Transform (FFT) shows that, iso-frequency slices of the temporal windows of 14ms and 28ms (fig 5-b, c and 6-a, b and c) succinctly illustrates the thickness and channel boundaries far better compare to temporal window of 56ms. Similarly, the 24Hz and 50Hz iso-frequency images at a temporal window of 14ms shows better results than the 64Hz frequency (fig 5). Furthermore, the 24Hz, 50Hz and 64Hz iso-frequency images at a temporal window of 28ms yields the best results for the subtle stratigraphic channels details with high resolution for this study than the 14ms and 56ms temporal windows respectively as in figure 6. However, the iso-frequency images of 24Hz, 50Hz and 64Hz at a temporal window of 56ms give the poorest seismic resolution and results in stratigraphic channel delineation in this study, probably due to the increase in the temporal window. The table 1 also shows the observed maximum and minimum amplitude values of iso-frequency seismic sections. The stratigraphic channel body, boundaries and thickness is clearly delineated at an estimated seismic amplitude range of 2.860 (minimum) to 65.464 (maximum) which correspond to iso-frequency sections with 28ms temporal window.

Table 1**.** Estimation of seismic amplitude of iso-frequency sections obtained from FFT method

| | 14ms temporal window | | 28ms temporal window | | 56ms temporal window | |
|---|---|---|---|---|---|---|
| Iso-frequency sections | Max amplitude | Min amplitude | Max amplitude | Min amplitude | Max amplitude | Min amplitude |
| 24Hz Iso-frequency section | 30.276 | 3.135 | 32.123 | 2.860 | 57.465 | 5.454 |
| 50Hz Iso-frequency section | 48.891 | 4.468 | 65.464 | 4.344 | 75.304 | 5.684 |
| 64Hz Iso-frequency section | 43.090 | 3.264 | 62.476 | 4.621 | 86.564 | 5.922 |

**4.2 Results of Seismic Attribute Analysis.**

To compliment the results of the spectral decomposition method e.g. Fast Fourier Transform (FFT), seismic attribute analysis was carried out based on semblance and curvature attributes. These seismic attributes have the characteristic property to x-ray the subtle stratigraphic channels in the 3-D seismic data. Thus, analysis of the results shows that, stratigraphic channel were detected both in semblance and curvature as in figures 8 and 9. However, stratigraphic channel features are distinctly delineated in curvature attribute calculation than semblance attribute; as such, curvature attribute performed better than semblance attribute in stratigraphic channels delineation in this study. To further discriminate the stratigraphic channels in-fillings such as sand versus shale lithologies, the results from the most negative seismic curvature attribute confirms the negative curvature anomalies seen as synclines or saggy in the channels as a result of differential compaction of the channels relative to its edges. We interpreted these negative curvature anomalies to be differential compaction of the softer channels infills, probably shale. Levees and channels edges appear as ridges in the horizon which is an indication of strong positive curvature anomalies.

## V. Conclusion

Fast Fourier Transform (FFT) as SD based method and seismic attribute analysis are two good tools for the detection of subtle or buried stratigraphic channels which play as potential hydrocarbon reservoirs. Based on the results obtained from the Fast Fourier Transform (FFT) algorithm and seismic attribute analysis of the 3-D seismic data in this study, the following conclusions were drawn.

- FFT proved to be a better method for stratigraphic channel's body, boundaries and thickness delineation especially at sub-seismic scale (as applicable in this study) than the seismic attributes analysis.
- Seismic attributes analysis also confirms the presence of subtle stratigraphic channels body and highlights it boundaries in the horizon of interest. Thus, it complements the spectral decomposition method adopted in this study.
- Seismic attributes analysis combined with other seismic interpretational methods could help in the determination of channel in-fillings.
- The horizon of interest under investigation in this study could be a prospective hydrocarbon reservoir in the Dutch Offshore F3-block. Therefore, the horizon is strongly recommended for further stratigraphic features detection that will enhance hydrocarbon reservoir delineation, exploration and exploitations.

## Acknowledgement

The authors would like to thank the dGB EarthSciences for making the data available via OpendTect share seismic data repository and Nigeria Agip Oil Company for providing the soft ware to encourage research and training in geosciences in Nigeria universities and Polytechnics.

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R. E. Ombu. "A Case Study on Horizon Based Stratigraphic Channels Delineation Using Fast Fourier Transform and Seismic Attributes: Implications for Reservoir Characterization." IOSR Journal of Applied Physics (IOSR-JAP), vol. 9, no. 5, 2017, pp. 18–28.