Journal of Energy Technologies and Policy
ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online)
Vol.4, No.9, 2014 www.iiste.org

Well Log Segmentation in Spectral Domain

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Abstract
Classic well log interpretation involves direct horizon mapping using log signature, attributes cross plot, etc to produce lithologic section for the delineation, exploration and production of hydrocarbon in oil and gas fields. The methods operate on recorded lithologic logs without adequate calibration. These result in interpretational ambiguities because of relatively poor resolution of well log owing to its recording in time, under sampling and coarse processing. In this paper, a new technique and algorithm for segmenting well log using discrete Fourier transform in the interpretation of well data obtained from the Niger Delta is presented. The aims and objectives of the study are to segment well logs into their constituent lithology in time domain, transform the well data from time to frequency domain and segment, and deduce viable diagnostic attributes such as magnitude, phase and frequency from the transform coefficients which could be used to identify the most probable zonation/contact in the well. The algorithm adopts Short time Fourier transform technique in the time to frequency transformation and is implementable on both standard and general seismic and well log interpretational platforms. It directly computes the spectral equivalent of the adopted lithologic log (Gamma-ray) and recovers hitherto lost frequency information. The results of the spectral decomposition of the well data yielded frequency (pseudo) logs that reveal subtle sub-well horizons and differences in lithology. By revealing masked horizons and better delineating and delimiting reservoirs, more hydrocarbons will be recovered and field development will be enhanced.
Keywords: Fourier transform, Spectral decomposition

1. Introduction

Well-log segmentation in spectral domain is the transformation and segmentation of well data into mineral contact zones in the frequency domain rather than in the traditional data acquisition time domain. Generally, well-log interpretation systems deal with the maintenance of a well log data base and evaluation of formation fluids but rarely carry out detailed stratigraphic interpretation. Standard well log interpretation involves direct horizon mapping, attributes crossplot, statistical analysis, etc. to produce lithologic section for the delineation, exploration and production of hydrocarbon in oil and gas fields. The methods operate on recorded lithologic logs (in time domain) without adequate calibration. These result in interpretational ambiguities because of poor resolution of the logs under sampling and coarse processing.

In this paper, the results of a new algorithm for segmenting well log in frequency domain using the discrete and short time Fourier transforms in the interpretation of well data obtained from Niger Delta are presented.

There are various strategies for addressing this segmentation problem. Classical approaches include the detection of abrupt changes in the mean (Webster, 1973) or in the variance (Gill, 1970; Hawkins and Merriam, 1973). General descriptions of these techniques are in Davis (1986). Recent studies include zonation by means of cluster analysis (Gill, Shomrony, and Fligelman, 1993), spectral analysis for identifying stationary intervals (Ligges, Weihs, and Hasse-Becker, 2002), etc.

Majority of the classic stratigraphic interpretation algorithms are structural, and the interpretation is based upon maximum cross-correlation of zones in wells. Cross-correlation techniques run into trouble, however, when stratigraphic units differ in thickness, or are truncated due to erosion, faulting, or thickness changes from differing rates of sedimentation. Stretching of zones alone or moving window correlation, or a combination of both cannot ensure geologically meaningful correlation. The techniques succeed only when data sets have favorable characteristics (Hawkins and Marriam, 1975). Also, existing commercial interpretational techniques and algorithms as reflected in oil and gas industry’s softwares are good, they are reliable only when geologic condition are favourable and need to be improved for precise reservoir delineation, delimitation and description. This is particularly necessary to improve the success ratio of field appraisal and identify potential exploration projects.

The main inputs to the method are well data and a clear knowledge of signal analysis and thin-bed tuning phenomena. The algorithm adopts short time Fourier transform technique in the time to frequency transformation and is implementable on both standard and general seismic interpretational platforms. It directly computes the spectral equivalent of the adopted lithologic log (Gamma-Ray) and recovers hitherto lost frequency information.

The results of the spectral decomposition of the well data yielded frequency (pseudo) logs that reveal subtle sub-well horizons and differences in lithology. By revealing masked horizons and better delineating and delimiting reservoirs, more hydrocarbons will be recovered and field development will be enhanced

2. Geologic Background

The Niger Delta is a large arcuate delta of the destructive, wave dominated type and is divided into the continental, transitional and marine environments. A sequence of under-compacted marine clay (Akata formation, depth from 11121ft) overlain by paralic or sand/shale deposits (Agbada formation, depth: about 7180-11121ft) is present throughout. Growth faults strongly influenced the sedimentation pattern and thickness distribution of sands and shales. The paralic interval is overlain by a varying thickness of continental sands (Benin formation, depth: 0- about 6000ft).Hydrocarbon is trapped in many different trap configurations, (Weber, 1987).

3. Theory

Fourier analysis is extremely useful for data analysis, as it breaks down a signal into constituent sinusoids of different frequencies. For sampled vector data, Fourier analysis is performed using the discrete Fourier transform (DFT). The fast Fourier transform (FFT) is an efficient algorithm for computing the DFT of a sequence; it is not a separate transform. It is particularly useful in areas such as signal and image processing, where its uses range from filtering, convolution, and frequency analysis to power spectrum estimation. Spectral decomposition techniques provide enhanced frequency resolution. The concept behind spectral decomposition is that a reflection from a thin bed has characteristics expression in the frequency domain that is indicative of temporal bed thickness (Amplitude Spectra) (Partyka, 1999). Amplitude spectra delineate thin bed variability via spectra notching patterns, which are related to local rock mass variability. Likewise phase spectra respond to lateral discontinuities via local phase instability. (Partyka, 1999).

Spectral techniques include discrete Fourier transform (DFT), Fast Fourier transform (FFT), Hilbert transform (HT), maximum entropy method (MEM) etc. The short time Fourier transform (STFT) was adopted in this study to overcome the inherent windowing problems of the above techniques..These problems complicate their resolution capabilities making them unreliable. (Castagna and Sun, 2003).

3.1 Discrete Fourier Transform (DFT)

The Discrete Fourier Transform (DFT) is the digital equivalent of the continuous Fourier transform and is expressed as

$$f(w) = \sum^{w=\infty} f(t)e^{-i\omega t} \qquad (2)$$

where, w is the Fourier dual of the variable‘t’. If ‘t’ signifies time, then ‘w’ is the angular frequency which is related to the linear (temporal frequency) ‘f’ (Yilmaz,2001).A key limitation of discrete Fourier transform is that it gives scalar attributes and an average representation of the frequency behavior of a whole seismogram without information as to the local concentrations of energy. This can be improved by the application of Short Time Former Transform (STFT) (Chakraborty and Okaya, 1995).

3.2 Short-Time Fourier Transform (STFT)

The Short-Time Fourier Transform (STFT) is a windowed Fourier transform and an analysis with fixed resolution. It maps a seismogram into a 2-D frequency-time plane. It is motivated by the need for a spectral representation that incorporates the time-varying properties of a non-stationary signal. Assuming the signal f (t) (time-domain seismogram) is stationary when seen through a window g (t) of limited extent, centered at time location (T), then the STFT is expressed as follows:

$$\sum f(t)\, g * [t - F]\, e^{-i2ft} \qquad (2)$$

‘g (t)’ is the window function, and ‘e-jwt’ is the Fourier kernel. This transform maps the signal into a 2-D function in a time-frequency plane (t, f). The STFT analysis depends critically on the choice of the window g(t). A key limitation of STFT is the fixed resolution obtained as a result of fixed window size although it provides improvement over the DFT. An improvement over the STFT is provided by the wavelet transform (WT).

3. Method

In this study, well-log segmentation and interpretation using signal transform technique was undertaken with well data from an oil field in Niger Delta. The transformation eliminates noise from the data and enhances contact recognition (zonation) and interval (zone) identification. In order to detect the subtle and other changes in the well data, the following routines: were adopted: (a) traditional lithologic plot and description in time (natural data acquisition domain), and (b) spectral analysis (frequency) using Discrete Fourier Transform (DFT) and Short Time Fourier Transform (STFT). The analysis was carried out using well of good data quality. The selected sand interval is from between 5490-5553ft (1.344-1.359 secs.) .In the transformation, fast Fourier transform (FFT) technique was used to compute response attributes and over entire window length for DFT, while in the case of STFT, it defines specific interval over which to operate. The STFT was computed within a gate of 8 data samples (±4 samples) bounding the top of sand interval and using a Gaussian function. Representative pseudo-well log attribute sections such as magnitude, frequency and phase were computed and plotted. The pseudo-sections computed from the results give distinct sequence boundaries, and lithofacies compartments. The original data, DTF and STFT attributes were correlated afterwards. In the displays vertical (across transforms) and horizontal (within transform) correlations were made. The original GR log was compared with each of the attributes of phase, frequency and magnitude. The marked locations within the reservoir serve as references for corresponding points on the spectral attribute for interpretation. The programming and plotting languages used are Matlab, Gnuplot and Surfer programs.

4. Discussion of Results

The data sets used are field data sourced from Niger Delta by Chevron Corporation, Nigeria. They include well Logs e.g. gamma-ray (GR), resistivity, self-potential, etc. and Seismic data. The well was analyzed for the trapping system and stratigraphic variation within a reservoir window defined by a low on Gamma-ray log, a high on resistivity log and a high on sonic. The sand interval under consideration is between 5490-5553ft corresponding to 1.344-1.359 seconds. The adopted lithologic log for analysis is GR log. In sedimentary formations, the log normally reflects the shale content of the formations. This is because the radioactive elements tend to concentrate in clays and shales.

Clean formations usually have a very low-level of radioactivity, unless radioactive contaminant such as volcanic ash or granite wash is present or the formation waters contain dissolved radioactive salts. It is useful for location of shales and non-shaly beds and, most importantly, for general correlation. The bed boundary is picked at a point midway between the maximum and minimum deflection of the anomaly. The radioactivities in sedimentary formations generally range from a few API units in anhydride or salt to 200 or more in shales. (Schlumberger, 1989). A low Gamma-ray count rate is diagnostic of a sandy formation while a high Gamma-ray count rate characterizes shale or radioactive sand (shaly sand) formation. In the case of resistivity log, a high resistivity indicates hydrocarbon presence or sand formation while a low indicates shale formation. The computed spectral attributes by DFT and STFT are magnitude, phase and frequency. The magnitude attribute is useful in highlighting bright spots, gas accumulation, sequence boundaries, major changes or depositional environments, major changes in lithology, faults, unconformity, thin bed tuning effect. The phase attribute is independent of amplitude and shows continuity and discontinuity of events. It shows bedding very well. Phase along horizon should not change in principle. Changes arise if the layer changes laterally due to certain phenomena like 'sink holes'. It is the best indicator of continuity or sequence boundaries. Frequency is an indicator of hydrocarbon or fracture zones by its low frequency anomaly. Frequency is also an indicator of bed thickness and lithologic parameters. Higher frequencies indicate sharp interfaces or thin shale bedding, lower frequencies indicate sand rich bedding.(Subrahmanyam and Rao,2008) Figure 1 shows Gamma-Ray plot over sand (reservoir) interval (5490-5553ft).The GR values are all indicative of sand but with varying degrees of shale intercalations making it impure at certain depths. The clean and shaly-sands are as shown In Figure 2, the variations of Gamma-Ray, Resistivity and Sonic logs within reservoir interval are shown. The reservoir interval defined by Gamma-ray log signature is between from 5490-5553ft (1.344-1.359 secs.).

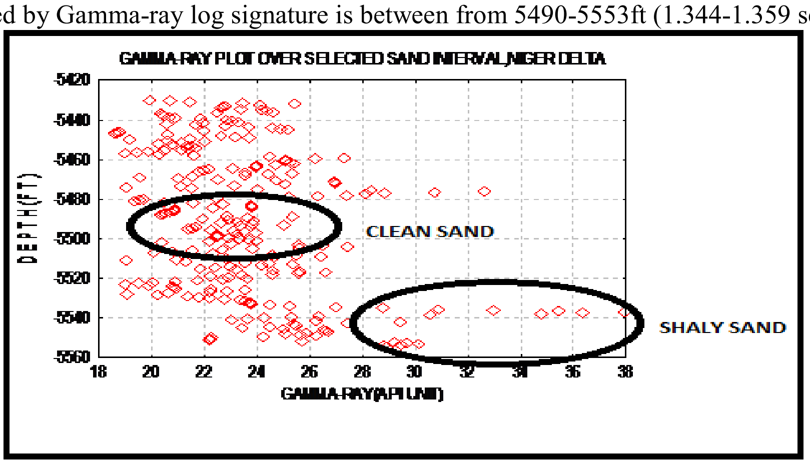


Figure 1. Gamma-Ray variation over sand (reservoir) interval (5490-5553ft).The GR values are all indicative of sand but with varying degrees of shale intercalations making it impure. The clean and shaly-sands are as shown.

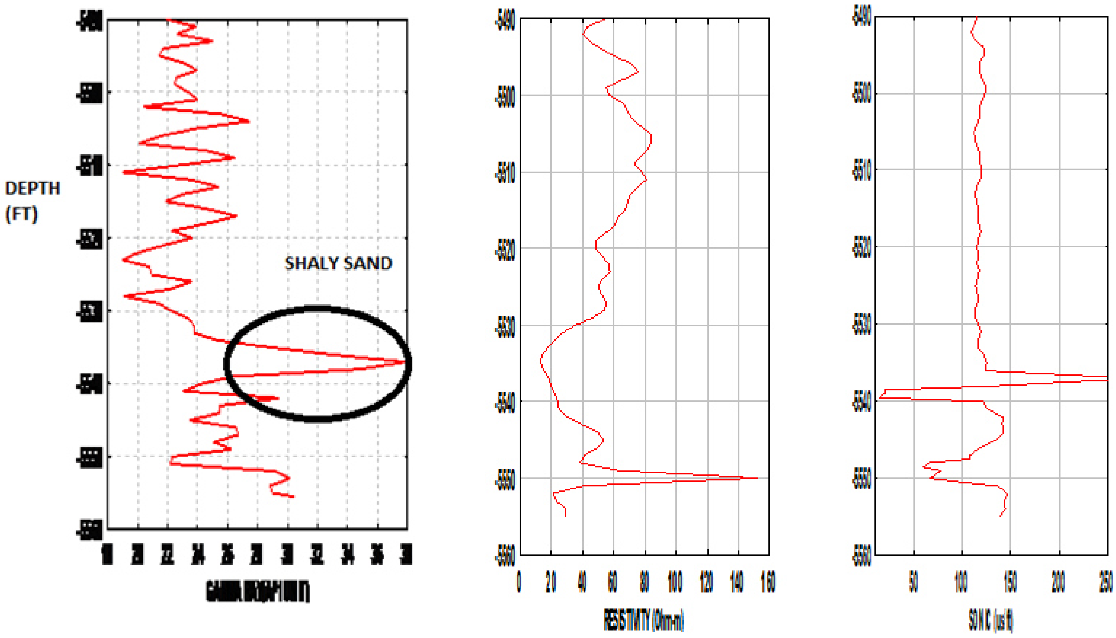
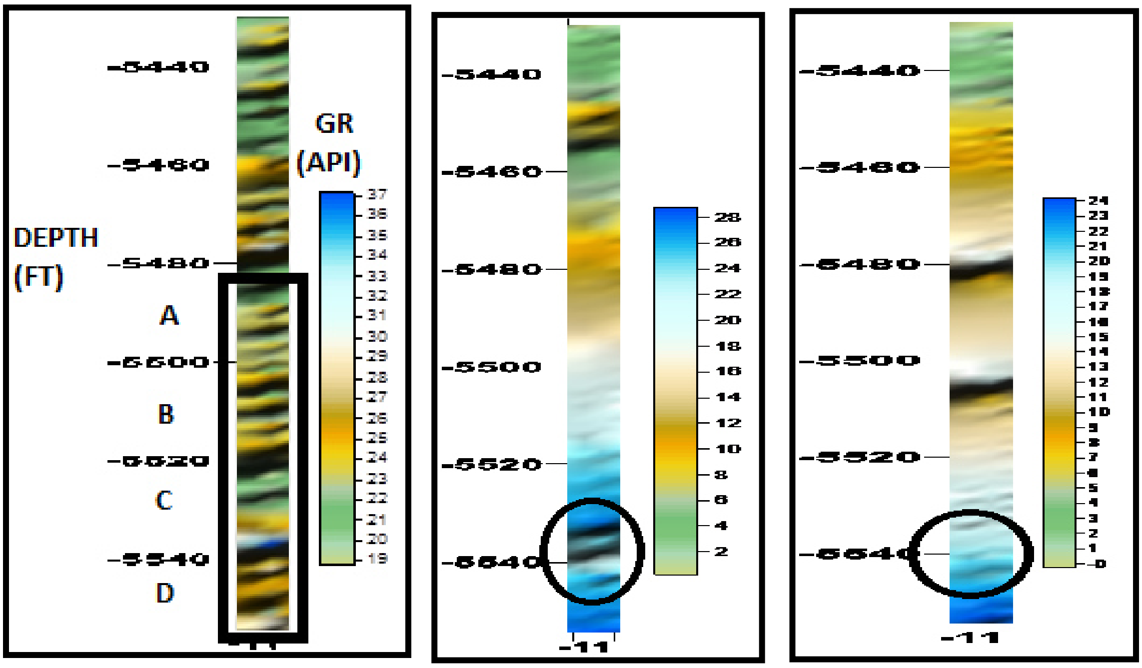


Figure 2. Variations of Gamma-Ray, Resistivity and Sonic logs within reservoir interval. The reservoir interval defined by Gamma-ray log signature is between from 5490-5553ft (1.344-1.359 secs.) .The prominent shaly sand unit is circled. The corresponding variations on the resistivity and sonic logs are evident



(a) GR Amplitude(API unit,(FT)) **(b) GR DFT Phase** **(c) GR STFT Phase**

Figure 3: Original noisy GR log and its corresponding DFT and STFT phase attribute. The delineated reservoir interval is: 5490-5553ft. Note that the mineral contact zones in the well at the corresponding level were clearly brought out in the phase attributes, particularly the STFT phase. The DFT is weakly diagnostic.

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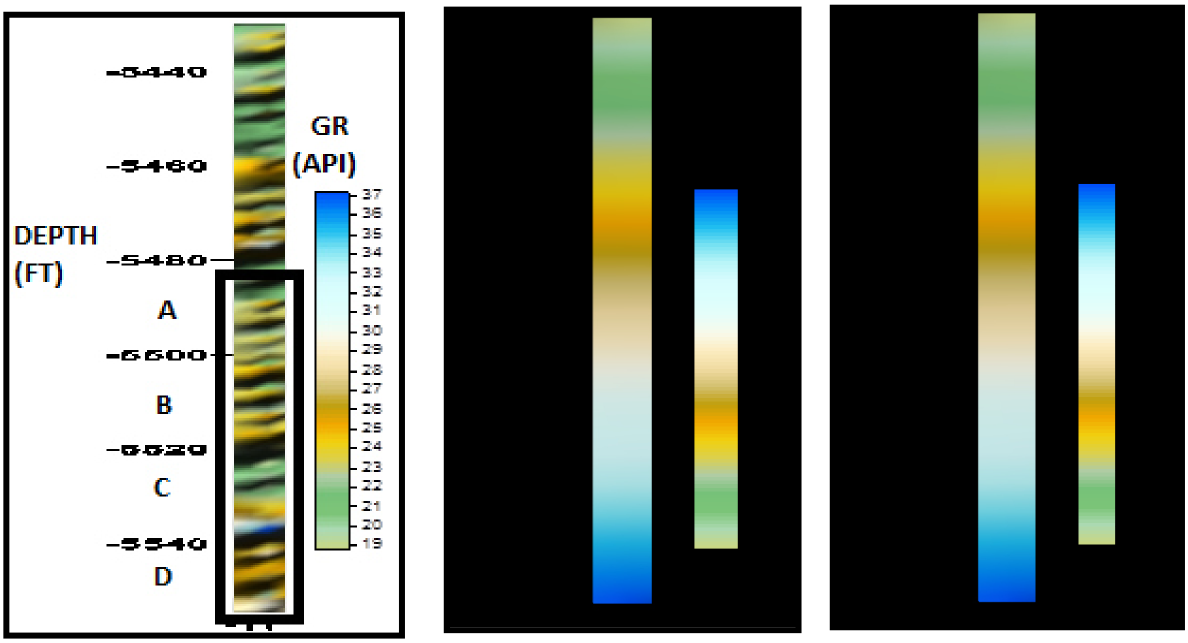
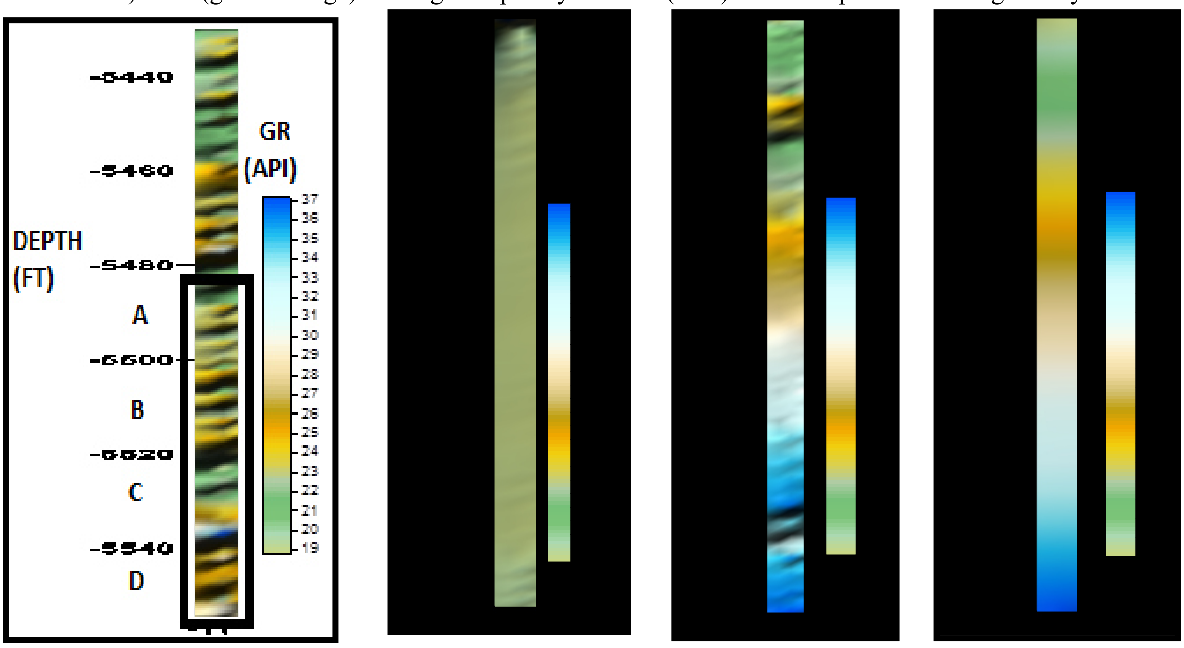
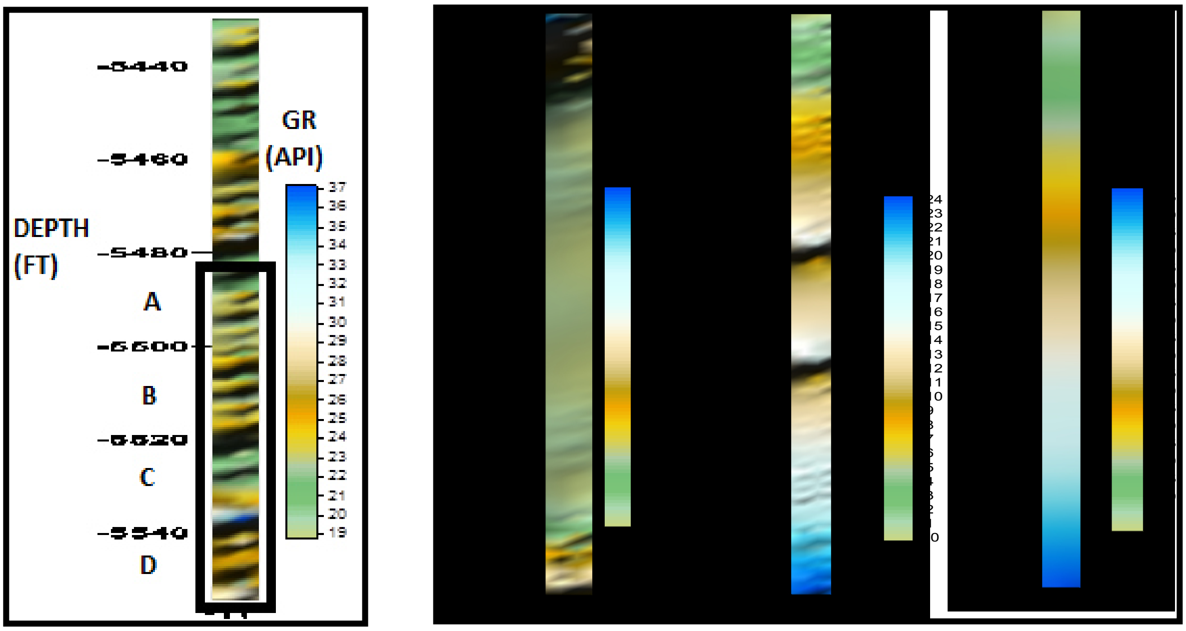


(a) GR Amplitude(API unit,(FT)) (b) GR DFT Frequency(Hz) (c) GR STFT Frequency(Hz)
Figure 4: Original noisy GR log and its corresponding DFT and STFT frequency attribute. The reservoir interval is: 5490 -5553ft .The frequency sections are similar but both show low frequency anomaly in sand (hydrocarbon or fractured) zone (green/orange) and high frequency in shale (blue). The true picture is that given by STFT.



(a) GR Amplitude(API unit,(FT)) (b) GR DFT Magnitude (c) GR DFT Phase (DEG) (d) GR DFT Frequency(Hz)
Figure 5. Horizontal correlation of attributes in DFT: Original noisy GR log and its DFT attributes of magnitude, phase and frequency. The reservoir interval is: 5490 -5553ft



(a) GR amplitude (Field data) (b) GR STFTmagnitude (c) GR STFTphase (d) GR STFTfrequency

Figure 6: Horizontal correlation of attributes in STFT: Original noisy GR log and its STFT attributes of magnitude, phase and frequency. The reservoir interval is: 5490 -5553ft .The exact segmentation in this study is that given by STFT as shown above.

Conclusions

In this paper, an algorithm for segmenting well log(Gamma-ray) in frequency domain using both the discrete and short time Fourier transform has been undertaken using well data from an oil field in Niger Delta. The aim of the study was to develop a practical spectral technique for segmenting well log. The objectives of the study were to segment well log into its constituent lithology in time domain, transform the well data from time to frequency domain and deduce viable diagnostic attributes such as magnitude, phase and frequency from the transform coefficients which could be used to identify the most probable zonation/contact in the well.

The algorithm adopted Fast Fourier transform (FFT) techniques in the time to frequency transformation and is implementable on both standard and general seismic and well log interpretational platforms. The transformation reduced noise in the recorded data and enhances the most probable contact recognition (zonation) and interval (zone) identification thereby giving reliable detail, better litho-zonation. It directly computes the spectral equivalent of the adopted lithologic log (Gamma-ray) and recovers hitherto lost frequency information.The results of the spectral decomposition of the well data yielded frequency (pseudo) logs that revealed subtle sub-well horizons and differences in lithology.

In conclusion, given that the literature on the use of high resolution spectral techniques on well log segmentation is limited, the new non-conventional approach will among other advantages reveal masked layers, better delineate and delimit reservoirs resulting in enhanced hydrocarbon recovery.

Acknowledgements

The authors wish to thank Chevron Corporation, Nigeria for making the well data available for use. Thanks are also due to the Federal University of Petroleum Resources, Effurun, Nigeria for the use of her computing facilities.

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