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The Application of Generalized Hilbert Transform for Faults and Stratigraphic Features in Niger Delta

Williams Ofuyah [1*] Olatunbosun Alao [2] Saleh Saleh[3] Kuma Ayua[4]
1. Department of Earth Sciences, Federal University of Petroleum Resources, Effurun, Nigeria
2. Department of Geology, Obafemi Awolowo University, Ile-Ife, Nigeria
3. Department of Petroleum Engineering and Geoscience,Petroleum Training Institue, Effurun, Nigeria
4 Department of Earth Sciences, Federal University of Petroleum Resources, Effurun, Nigeria

Abstract
Faults are critical to the accumulation of hydrocarbon and manifest themselves as abrupt, gradual or gentle changes of seismic amplitude. However an important element of entrapment is the presence of numerous subtle faults whose identification with computer–based algorithm poses a major challenge. Traditionally, edge detection techniques such as coherence, semblance, Hilbert transform (HT), etc are employed in evaluating faulted hydrocarbon prospects by examining trace to trace similarity in data and to unmask subtle events. However, these have high sensitivity to noise and suffer from computational truncation, and are therefore unreliable. This study focuses on the application of generalized Hilbert transform (GHT) of seismic amplitude data in the interpretation of 3D seismic data from the Niger Delta. The GHT is a windowed conventional Hilbert transform. It extends the HT by introducing a window and an order. HT is of order one, and one of the possible orders of implementation of the GHT. The GHT is less sensitive to noise and gives better resolution of subtle features than conventional edge detection techniques. The algorithm adopted is based on fast Fourier transform techniques and was developed from basics and outside oil-industry interpretational platforms using standard processing routines. Preliminary results of the algorithm, when implemented on both oil-industry and general interpretational platforms gave convincing images. The generalized Hilbert transform of the thin bed reservoir revealed subtle faults and provided an enhanced level of evaluating a prospect. This is capable of improving reservoir production and performance.
Keywords: Fourier, Hilbert transform, Spectral decomposition

Introduction

Geologic discontinuities such as faults and fractures in 3-D seismic data manifest themselves as abrupt, gradual, and subtle changes of amplitudes. The techniques for identifying abrupt and gradual changes have been provided by authors such as Partyka et al, 1999) (Spectral decomposition), Walden (1994) (spatial clustering for edge detection), etc. The introduction of the 'coherence cube' by Bahorich and Farmer(1995) has resulted in the publication of new fault detection technologies such as Marfurt et al 1998). Luo et al(2003) described the application of the technology using different algorithms with varying degrees of resolution capabilities

Among the several advantages offered by discontinuity detection algorithms such as seismic coherency,Hilbert transforms etc are the ability to carefully analyze structureal and stratigraphic features over an entire data volume including zones that are shallow,deep and adjacent to the primary zone of interest,identify and interprete subtle feature that are not representatable by picks on peaks,troughs,or zero-crossings,generate paleo-environmental maps of channels and fans corresponding to sequence versus reflector boundaries,etc (Marfurt et al 1998).

Faults are critical to the accumulation of hydrocarbon and manifest themselves as abrupt, gradual or gentle changes of seismic amplitude. However an important element of entrapment is the presence of numerous subtle faults whose identification with computer–based algorithm poses a major challenge(Downey,1990). Traditionally, edge detection techniques such as coherence, semblance, Hilbert transform (HT), etc are employed in evaluating faulted hydrocarbon prospects by examining trace to trace similarity in data and to unmask subtle events. However, these have high sensitivity to noise and suffer from computational truncation, and are therefore unreliable. This study focuses on the application of generalized Hilbert transform (GHT) of seismic amplitude data in the interpretation of 3D seismic data from the Niger Delta. The GHT is a windowed conventional Hilbert transform. It extends the HT by introducing a window and an order. HT is of order one, and one of the possible orders of implementation of the GHT. The GHT is less sensitive to noise and gives better resolution of subtle features than conventional edge detection techniques. The algorithm adopted is based on fast Fourier transform techniques and was developed from basics and outside oil-industry interpretational platforms using standard processing routines. Preliminary results of the algorithm, when implemented on both oil-industry and general interpretational platforms gave convincing images. The generalized Hilbert transform of the thin bed reservoir revealed subtle faults and provided an enhanced level of evaluating a prospect. This is capable of improving reservoir production and performance.

The main conclusion is that GHT has enhanced resolution capability resulting in improved geologic maps. This has application in the localization of thin-bed reflections and definition of bed thickness variability within complex and rock strata including the detection of subtle discontinuities like facies change,channels,microfaults,reflection-free events within large 3D volume. The key inputs are the concepts and practices of seismic stratigraphy,principles of spectral decomposition,clear knowledge of signal analysis and thin-bed tuning phenomena and properly migrated seismic data.

Geologic Background

The Niger delta is one of the most prolific oil producing areas in the world. It is located in southern Nigeria between latitudes 3^0N and 6^0Nand longitudes $4^0 30^1$ E and 9^0E. The delta covers an area of about 105,000km^2. The Niger delta is a large arcuate delta of the destructive wave dominated type and is divided into the continental, transitional and marine environments comprising braided streams,meander belts systems,floodplains,barrier bars etc. A sequence of under compacted marine shale (Akata formation, depth from 11121 ft) is overlain by paralic or sand/shale deposits (Agbada formation, depth from 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 from 0-6000ft).. Most of the hydrocarbon are in the sandstones of the Agbada formation,mostly trapped in roll-over anticlines fronting growth faults. (Short. and Stauble, 1967) The reservoirs are typically channels and barrier sandstones bodies.Merki(1972) noted that the age of the formations become progressively younger in a down-dip direction and ranges from Paleocene to Recent.

2.Theory of Hilbert and Generalized Hilbert Transforms

Hilbert Transform (HT)

The Hilbert transformation is a filtering operation that passes the amplitude of the spectral components unchanged but alters the phases of the spectral components by the ninety degrees (Π/2). Given F(w) as a complex function ,F(w) can be expressed in terms of its real ($F_r(w)$ and imaginary $F_i(w)$ components in the form

$F(w)=F_r w)+iF_i(w)$ (1)

Where F_i (w) is the Hilbert transform of Fr (w). (Yilmaz, 2001).

The instantaneous amplitude (envelope or reflection strength), instantaneous phase and instantaneous frequency have expressions similar to the Fourier derivatives. The Hilbert transform is sensitive to noise and suffers from computational truncation..The truncated Hilbert operator is an exact implementation based on GHT ,but an approximation in the traditional HT. . (Luo et al, 2003).

The Generalized Hilbert Transform (GHT)

If f(t,w) is the Fourier transform of an input trace, the nth -order Generalized Hilbert transform can be written as

$Yi(t)=(2*\Sigma_W[Im(F(t,w)])^n]^{1/n}$ (2)

The real component is expressed as

$Yr(t)=[2*\Sigma_W(Re[F(t,w)])^{n+}Re(F(t,0))^n]^{1/n}$ (3)

The GHT is defined as a windowed conventional Hilbert transform and it extends the HT by introducing a window and an order. Hilbert transform is of order one, and one of the possible orders of implementation for the generalized Hilbert transform. . (Luo et al, 2003).

GHT improves the HT in two ways:

(a)GHT has different orders, n, of computation (n=1, 2…), adjustable window shapes and widths. The conventional HT is only one (n=1) of the many possible implementations of GHT.

(b) GHT is less sensitive to noise and gives better resolution of subtle features than conventional edge detection techniques. (Luo et al, 2003).

3. Method

The main objective of our study was to develop a practical technique for mapping subtle stratigraphic units and faults.. The data set used comprises seismic and well data sourced from Niger Delta by Chevron Corporation, Nigeria

In order to detect the subtle and other changes, the following routines, namely Structural interpretation (time) (for data reconnaissance and comprehension), enhanced geologic transformations (also in time) and Spectral analysis (frequency) using DFT, HT, and GHT were adopted.

Three classes of data were created from the field data after loading into the Kingdom Suite Package and extracted. These are 2D data along an arbitrary line created to tie the entire six (6) wells in the survey to enhance the hard data information, 3D sub-volume (i.e. for reservoir window with top: 2.752s, base: 2.768s) and entire data cube. The segmentation was to facilitate detailed investigation. In the spectral domain, fast Fourier convolution techniques (FFT) were employed.. The interpretation techniques adopted and their order of application is:

(a) Structural interpretation of 2D, and 3D data
(b) Time- frequency (spectral decomposition) transforms.

The conventional techniques of structural, DFT, HT were initially applied to data to understand amplitude anomalies in data acquired from wells and inter-well regions using the constructed arbitrary line. Having known the strengths and weaknesses of the conventional spectral techniques, they were then extended e.g. extension of HT to GHT . The HT was extended to GHT, in order to overcome its limitations while retaining its desirable characteristics. The initial application was to the arbitrary seismic line (representing 2D, followed by the three dimensional (3D) application of the transforms to the delineated thin–sand reservoirs embedded in the dense 3D data

While the DFT and HT spectra were computed over the entire time window (0-6secs), the GHT was computed within a gate of 40ms ($\pm$ 20ms), bounding the top and base of sand ((i.e reservoir window: 2.752-2.768s, 16ms thick).,. The stratigraphic features were analyzed over a narrow temporal window as defined by the maximum usable frequency in the input seismic data. Both techniques (conventional and developed) were applied to the thin-sand reservoir and the outputs compared. The associated parameters used for investigation are a Gaussian window function and GHT of second order (i.e. n = 1, 2).

The algorithms were developed from first principles and by extension of the conventional techniques and their superiority is evident from the results obtained as shown for the case of the volume (3D) data under discussion

The displays show spectral characterization of the 3D data using HT and GHT and their spectral attributes of amplitude, envelope (instantaneous amplitude), instantaneous frequency, and instantaneous phase maps in frequency domain each with peculiar characteristics. The softwares used comprise standard and developed programs. The standard interpretation seismic software (Kingdom Suite,Version 7.3) was made available for use at the work station facility of the Department of Geology Obafemi Awolowo University, Ile-Ife. The standard processing program used was Kingdom Suite (Version 7.3),while Matlab (Version 7.0), Pascal (Version 7.0),used are general platforms

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.

The computed spectral attributes by HT and GHT are amplitude,envelope phase and frequency. The envelope 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 instantaneous 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. The instantaneous 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

The base map of the survey and in it is the arbitrary line.Figure 2 is the interpreted arbitrary line showing two major faults,F1,F2 across the delineated reservoir window and all the six wells in the field(top of section). Figure 3 shows the spectral characteristics of the arbitrary line at the top and base of the reservoir. The maximum useful frequency(Nyquist) in the 2D data is about 30Hz

The Hilbert transform (HT) and L^2 order Generalized Hilbert transform (GHT) results are presented in Figures 4-8,most of which are for the reservoir top In Figures 4 and 5, it can be seen that the GHT envelope and amplitude maps give better definition of the stratigraphy than both the original and HT maps.Te North –South delineation of the channel and its tributaries or dendritic patterns arises from its phase discontinuities or faulting(Figure 5) The phase map (Figure 6) clearly shows that the tops of wells 03 and 06 are within channel, whereas it is not the case with the HT display. While the HT phase values of 0^0 or $\pm$ 180^0 (Green and Light Blue) indicate thickness (highs) of the bed in block, the GHT phase (Blue, Red) distinctly shows the undulating surface. The channels are also clearer. It can be seen on the GHT and HT instantaneous frequency maps in Figures 7 and 8 that the accurately located wells (01, 04, and 05) were sited where frequency values are within 0-25Hz (Green) on the GHT map. This is consistent with and within both the GHT useful bandwidth (0-31 Hz) and the Nyquist frequency. On the HT frequency map, the corresponding locations have frequencies values that are smeared (Yellow, 15-25Hz, and 34-46Hz). Recall that the useful bandwidth of HT is 34-40 Hz,green. This implies signal (tuning amplitude) suppression due to noise. New prospective zones can be inferred from the Green locations on the GHT map. The GHT encompasses all the frequency values of the HT, and even close to the useful frequency.Such continous and wide frequency recovery is only possible in recorded well logs,but this is localized(not field wide) The frequency maps for top and base of sand are presented for illustration(Figure 8). The trend of the shale lineaments (Red) is distinct here. The GHT envelope map gives the clearest images of the top amplitude in most respects. For instance, the shale lamination below well 03 is absent on HT amplitude maps, but present on those of GHT. Other distinguishing events such as channel patterns can be seen.The frequency maps also reveal the presence of channels. Note that the producing wells are located within the frequency tuning limits(0-31Hz). It can be seen from the arbitrary line spectra and GHT maps (Figure 5) that at this time level (2.752 seconds), wells 02, 03, and 06 are in shale embedded in sandstone bodies . In addition, GHT amplitude indicates that the entire wells were located on the bank of the channels, while the GHT frequency values at locations outside the wells are outside the tuning amplitudes. All the locations are, with the exception of the base of sand in wells 03 and 06, of the same lithology on the original display. Prospective zones are evident on the West and South-West of well 05, South-West of well 06 and North-East of well 03 (Figures 5,7 and 8). The channel earlier discussed is also apparent. These locations are masked on the original amplitude display. The L^2 order GHT gives better definition of the events than the HT. On the GHT/HT instantaneous frequency displays (Figures 7 and 8) at time 2.752 seconds, well 02 is in shale (GHT), but masked on the HT instantaneous frequency. The same holds for the sand at 2.768(base) in wells 03 and 06, as obtained for DWT. Zones of low frequency values indicative of presence of hydrocarbon, can be seen to the South-West, West and South-East areas. The significance of this analysis for exploratory work is that poor interpretation of data results in wrong location of wells, reservoir by-pass and hence slow field development. Each attribute computed from the algorithm provides new and different but convergent information all of which, when integrated, aids in well planning location and field development. The study reveals that sand is compartmentalized with shale inter-bedding and non-sand lithofacies intercalations, and that the reservoir is of the channel type, typical of many reservoirs in the Niger Delta. In addition, a negative relief deduced (beyond well 02), and a positive one (beyond wells 03 and 06) indicate a depression or valley. Again, the wells were located at the banks of the channels and faulting occurred at the locations of line 5840 (corresponding to the negative relief), and at line 6100 (positive slope)..The circled spots on the original amplitude and other maps are sample reference locations for interpretation. Others can be inferred.

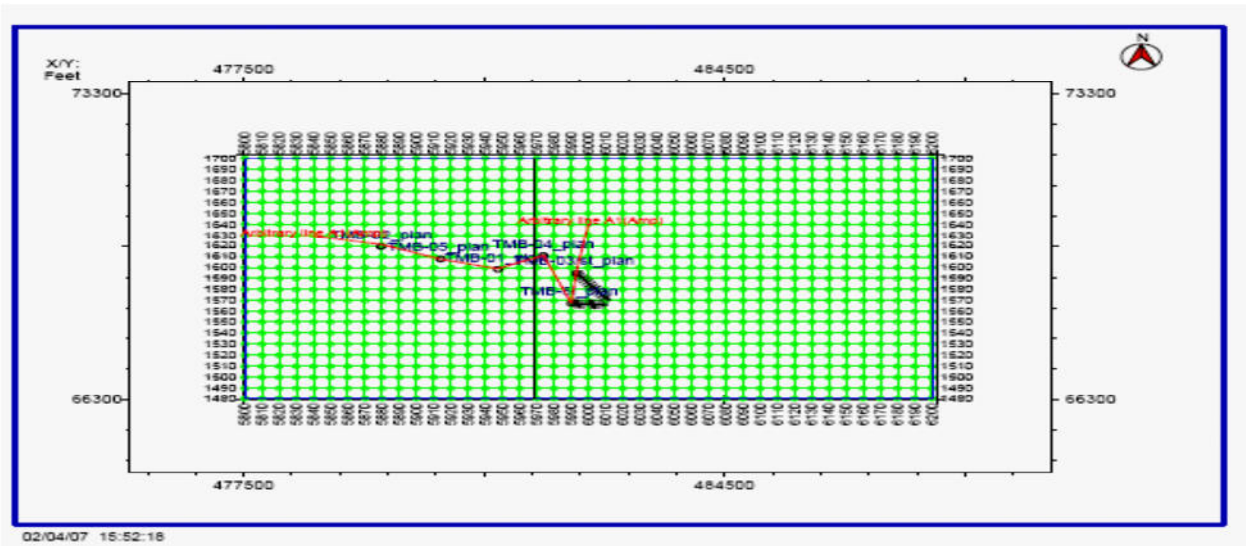


Figure 1: 'X'-Field, Niger Delta. **:** Base map of survey area showing the arbitrary line (red).The Arbitrary line connects the entire wells (six) in the survey.

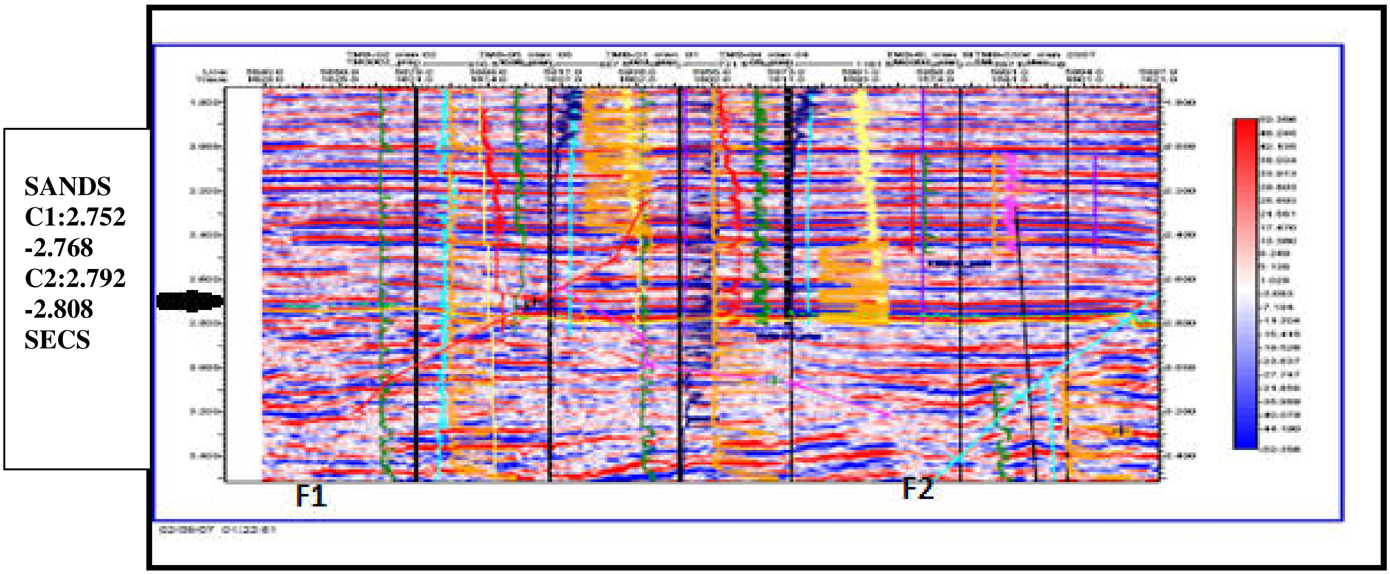
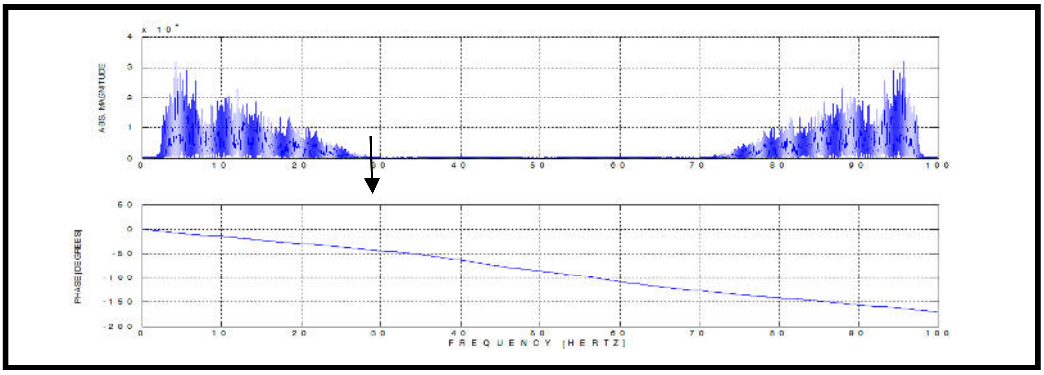
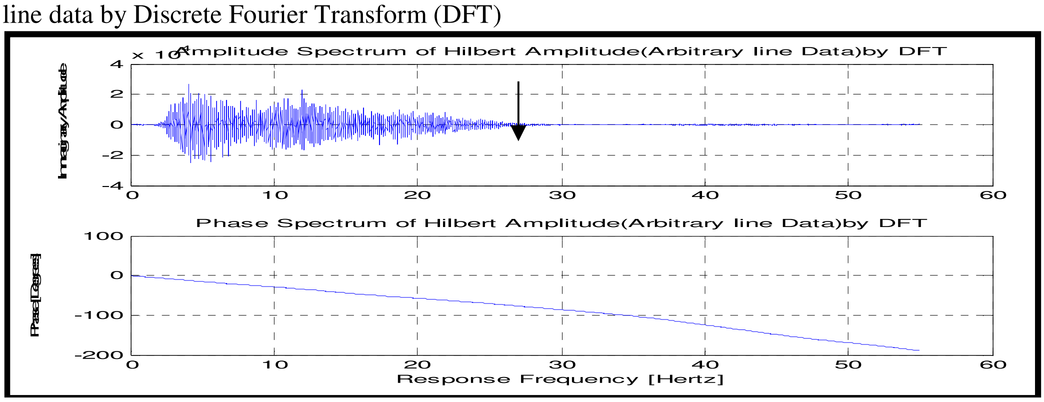


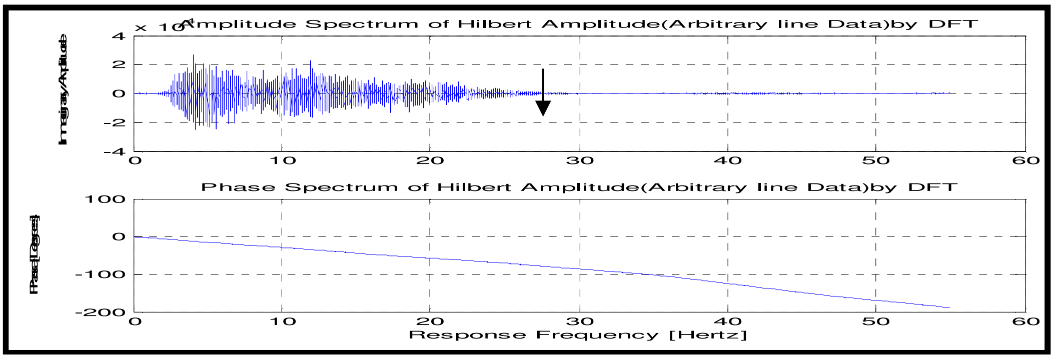
Figure 2. 'X'-Field, Niger Delta: Arbitrary line after interpretation: Two major faults ,F1,F2 are shown bounding the wells at the reservoir interval under analysis (2.752-2.768 secs).The well locations are indicated



(a)Top of Reservoir(2.752 s): Amplitude and Phase Spectra of original Arbitrary line data by Discrete Fourier Transform (DFT)

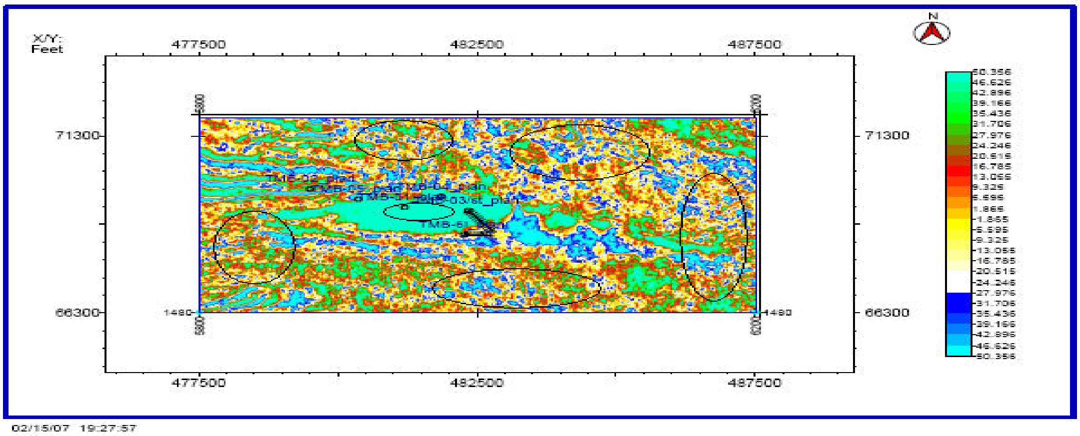


(b)Top of Reservoir (2.752 s): Amplitude and Phase Spectra of Arbitrary line by Hilbert transform (**HT**)

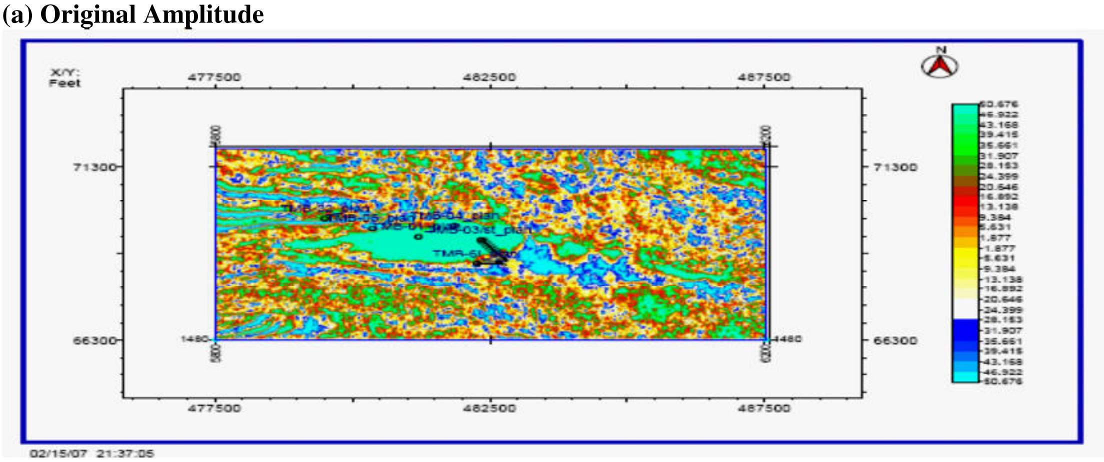


(c)Base of Reservoir (2.768 s): Amplitude and Phase Spectra of Arbitrary line by Hilbert Transform **(HT)**

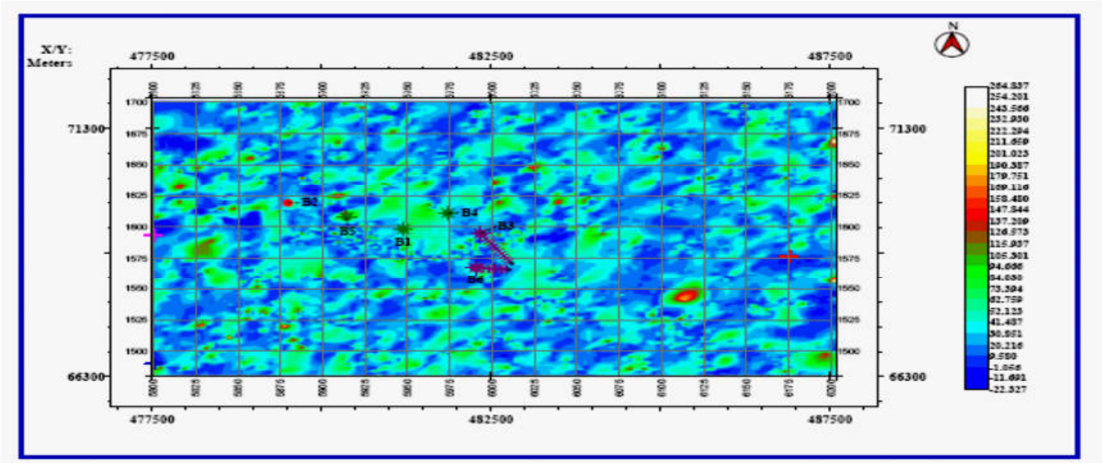
Figure 3: 'X'-Field, Niger Delta: Spectral characteristics Arbitrary Line (a) Top of Reservoir (2.752 s) : (a) Amplitude and Phase Spectra of original Arbitrary line data by Discrete Fourier Transform (DFT), (b)Amplitude and Phase Spectra of Arbitrary line by Hilbert transform (HT) . **(c)Base of Reservoir (2.768 s):** Amplitude and Phase Spectra of Arbitrary line by Hilbert Transform (HT).The maximum useful frequency is about 30z.



(a) Original Amplitude

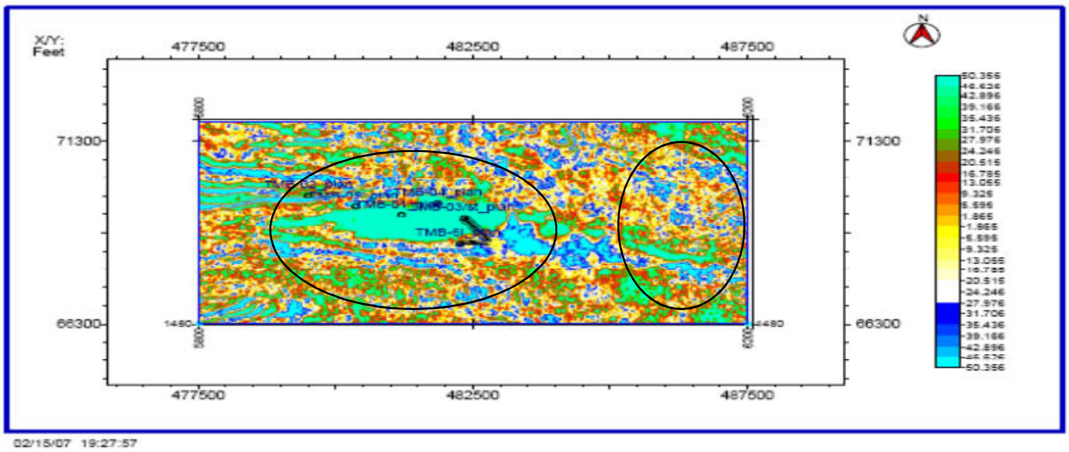


(b) HT Amplitude of (a).

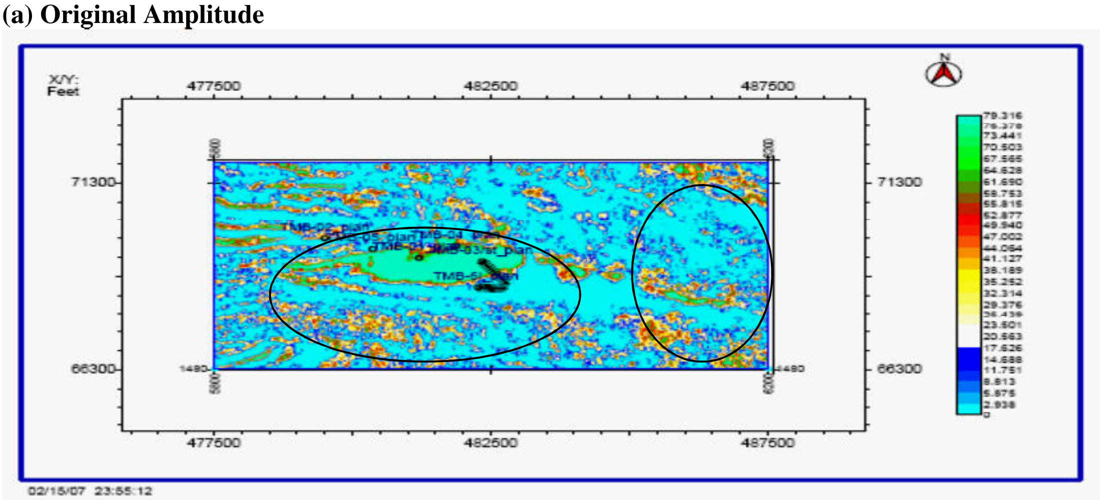


(c) L^2-Order GHT Amplitude of (a)

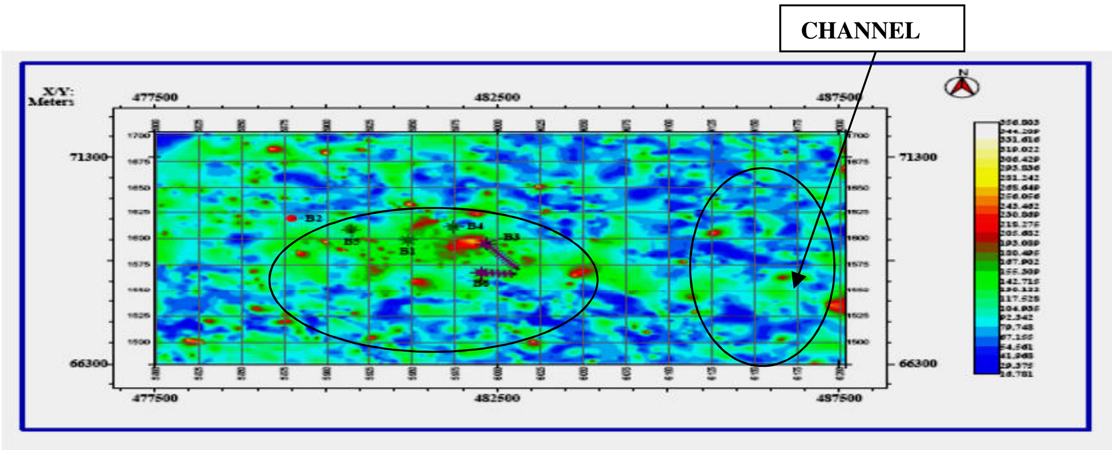
Figure 4 : 'X'-Field, Niger Delta , Sand Top, 2.752 Secs.). 3D: (a) Original Amplitude (b) HT Amplitude of (a). (c) (h) L^2-Order GHT Amplitude of (a).The sand zones(reen colour) are better imaged on the GHT display, revealing prospective zones



(a) Original Amplitude

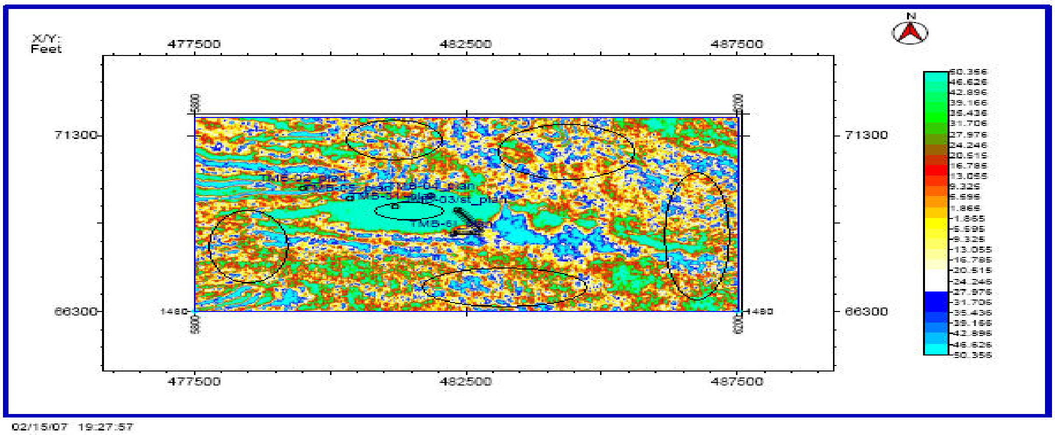


(b)HT Envelope (Instantaneous) Amplitude

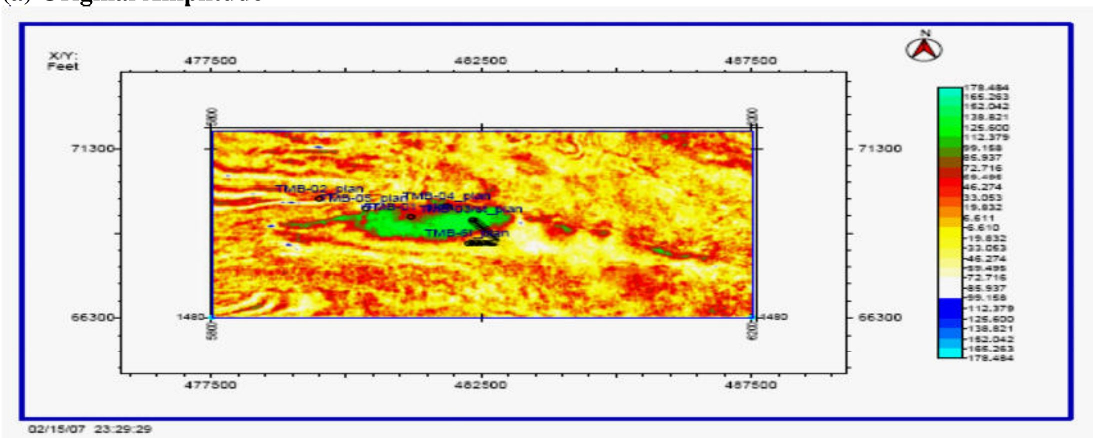


(c) GHT Envelope

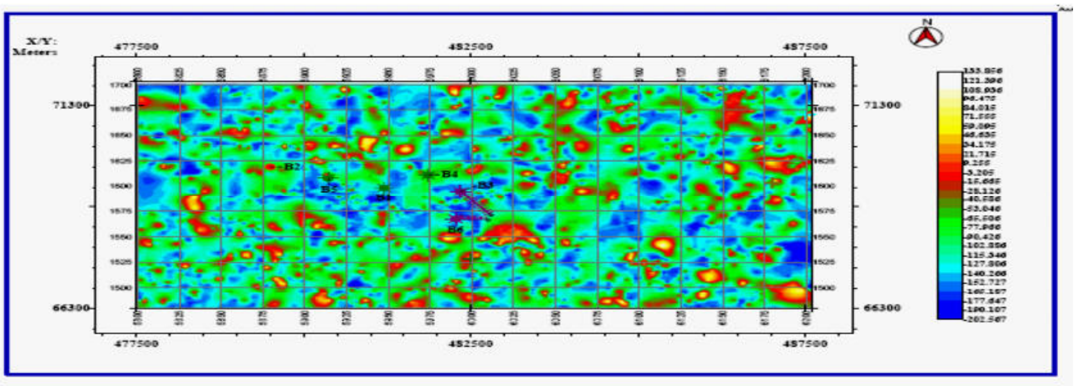
Figure 5: 'X'-Field, Niger Delta , Sand Top, 2.752 Secs.). 3D: (a) Original Amplitude (b)HT Envelope (Instantaneous) Amplitude of (a). (c) L^2-Order GHT Envelope of (a)This indicates bright spots and major changes in lithology.The channel and other stratigraphic features are most evident on the GHT map



(a) Original Amplitude

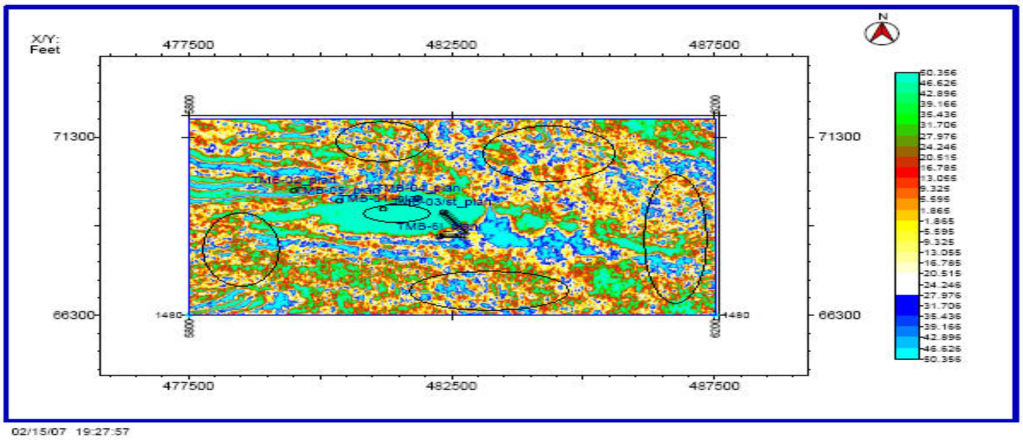


(b) HT Instantaneous Phase of (a).

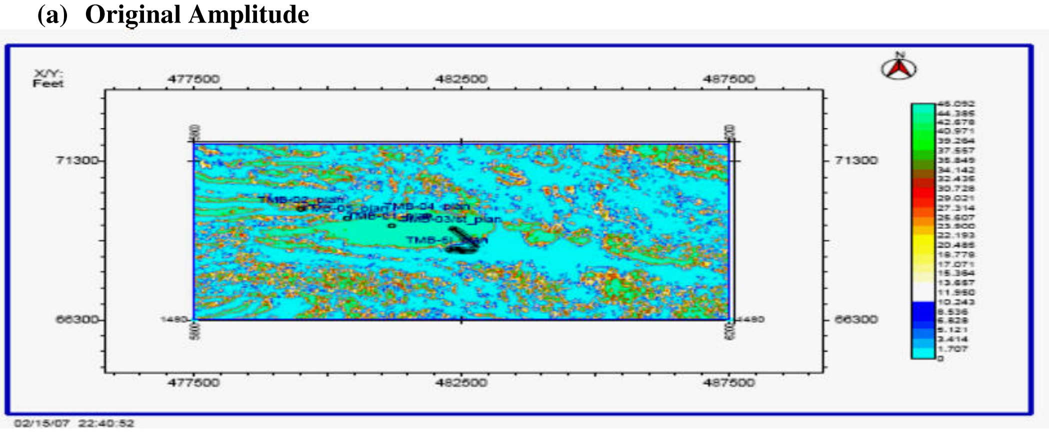


(c) L^2-Order GHT Instantaneous Phase of (a).

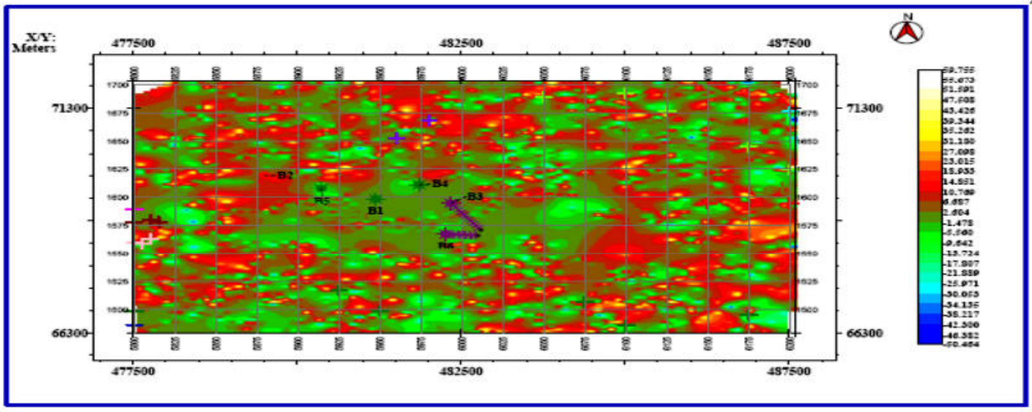
Figure 6 : 'X'-Field, Niger Delta , Sand Top, 2.752 Secs.). 3D: (a) Original Amplitude (b)HT Instantaneous Phase of (a).(c) L^2-Order GHT Instantaneous Phase of (a).Phase shows edges (continuity or discontinuity) of events. The green and blue colours represent the sand /hydrocarbon zones on the GHT, while only the green colour represents sand on HT.The segmentation is enhance by small phase values on the GHT



(a) Original Amplitude

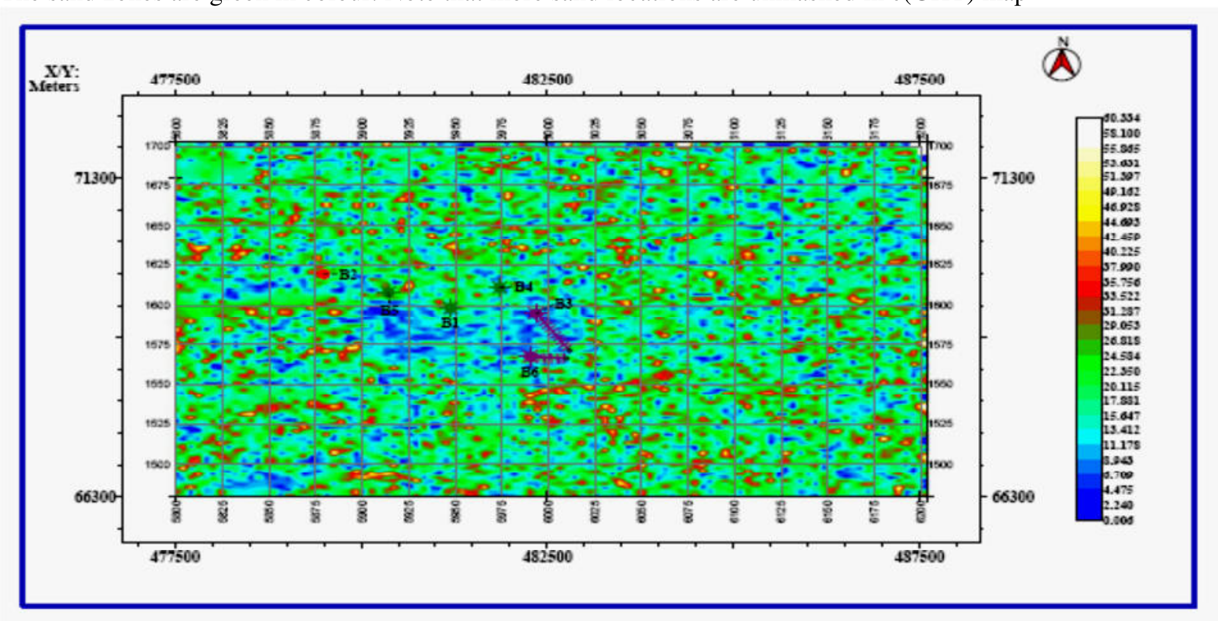


(b)HT Instantaneous Frequency

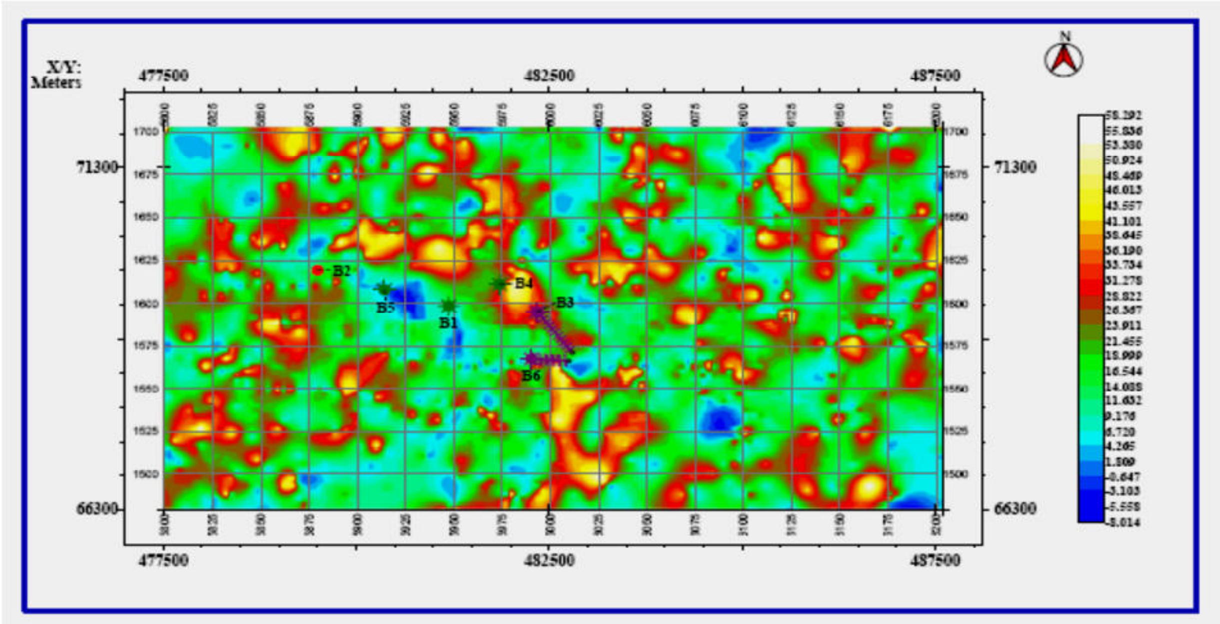


(c)GHT Instantaneous Frequency (IDP)

Figure 7: 'X'-Field, Niger Delta , Sand Top, 2.752 Secs.). 3D: (a) Original Amplitude (b) b) HT Instantaneous frequency of (a).(c) L^2-Order GHT Instantaneous frequency of (a).The frequency attribute indicates hydrocarbon or fracture zones in view of its low frequency anomaly. The sand zones are green in colour. Note that more sand locations are unmasked in c(GHT) map



(a)GHT Instantaneous Frequency (Top, 2.752 secs, Positive Frequ)



(b) GHT Instantaneous Frequency(Base 2.768s Positive Frequ,)

Figure 8: 'X'-Field, Niger Delta, Volume Data (3D), and GHT FREQUENCY MAPS. (Positive frequency),(a)Sand,Top,2.752secs)GHTInstantaneousFrequency.(b)Base.2.768 s GHT Instantaneous Frequency.. The sand zones are the blue and green portions, in view of their low frequency anomaly, while the shale zones are the red and yellow portions.

Summary

The spectral properties of field data show that the frequency tuning of the attributes of the transforms correlates well with zones of drilled wells of good data quality. An illustration of the amplitude tuning and useful frequency range for each of the transforms, using the top of sand C1 as example, is shown below:

While the Nyquist(maximum useful) frequency in the data is **37 Hz,** the useful bandwidths recovered for each of the transforms for the reservoir ,

e.g. **(top),** are: **HT** (3-27Hz [2D], 34-40Hz [3D]), **GHT** (0-31Hz [3D])

The values for the **base (3D)** are: **GHT** (0-28 Hz)

This suggests more log-type (geologic)-frequency recovery from seismic for GHT. GHT is stable, exact, and better resolving resolving than HT, an approximation. The windowing provided by the GHT overcomes the limitations of the HT.

The instantaneous attributes computed with the GHT are amplitude, phase and frequency like the HT. Although the GHT was computed for orders n=1, 2, 4 and 6, the limited analyses indicate that the resolving capacity appears to increase with the order of computation. Although the L^1-order GHT is equivalent to traditional HT in theory, their comparison shows that the L^1-order GHT gives clearer image. A reason for this is the computational truncation suffered by HT.

The GHT is stable, less noisy and captures stratigraphic features such as faults and fractures, not detected by HT. It is therefore good for edge detection. Prospective zones with GHT attributes, having convergent information consistent with established indicators, are evident.

While whole time gate was used for the HT, the GHT utilized sub-volume data at reservoir level. The transformation was done within a window of 40 ms(± 20 ms) centered at top and base of the reservoir:

5. Conclusions

In this study, an application of HT and GHT for faults and stratigraphic features with example taken from Niger Delta has been undertaken. The aim of the study was to develop a high resolution and optimal technique for mapping stratigraphy which is usually masked after normal data interpretation with a view to characterizing hydrocarbon reservoir. The overall objective was to provide more accurate solutions to the geologic problems of uncertain determination of reservoir geometry, connectivity and flow units, stratification and depositional sequence in order to facilitate the drilling of wells with improved confidence. Although the oil fields of the Niger Delta are characterized by structural and stratigraphic traps or a combination of the two, the reservoirs of interest are those that are of low amplitude or subtle geologic features often bypassed or hidden on conventional displays. Recent studies indicate that they constitute giant prospects. The application of non-conventional technique of GHT resulted in better geologic maps by recovering hitherto masked log-type low frequency(stratigraphic) information leading to an improved understanding of subsurface geology and reservoir architecture. By comparing the features on both the conventional and non conventional techniques with respect to noise level, noise sensitivity is evident for the conventional techniques, whereas the GHT images are stable and clearer.

A key requirement for successful implementation of the algorithm is that the processing and analysis efforts must be sincere by a clear understanding of the phenomena that distort seismic amplitudes and the theory of signals. When this is the case, GHT and analysis of seismic data in combination with the classical methods can be a powerful practical tool to quantitatively map reservoir architecture. On the other hand, if the analysis lacks integrity, the technique can very well stand for obscurity, and meaningless. This is crucial in complex geological settings such as geological edges, reflection-free hydrocarbon habitats and frontier areas. The integrated technique is fast, and low in expense. Thus, the investigation of the Miocene-age (6.1MY) thin bed reservoir yielded frequency maps that revealed significant sub-seismic faults, channel and valley system.

Acknowledgements

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Instantaneous Phase of (a).(c) L^2-Order GHT Instantaneous Phase of (a).

Figure 7: 'X'-Field, Niger Delta , Sand C1, Top, 2.752 Secs.). 3D: (a) Original Amplitude (b) b) HT Instantaneous frequency of (a).(c) L^2-Order GHT Instantaneous frequency of (a).

Figure 8: 'X'-Field, Niger Delta, Volume Data (3D), GHT FREQUENCY MAPS. (Positive frequency),(a)Sand,Top,2.752secs)GHTInstantaneousFrequency.(b)Base.2.768 s GHT Instantaneous Frequency.