A Comparative Study of Thin-Bed Interpretation using Spectral and Cepstral Transform Techniques in Dense 3D Seismic Amplitude Data in Niger Delta

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Abstract:- The purpose of this study is to develop a unique, high resolution and optimal technique for mapping stratigraphy which is usually misinterpreted after data interpretation using highly resolving signal transforms. This is with a view to characterizing and evaluating hydrocarbon reservoirs. The key objectives are to: build efficient workflow algorithms and computer program codes from basics (mathematical functions) for spectral decomposition including each of its extensions using the Discrete Fourier Transform (DFT), Cepstral Transform (CT) and apply it to a very thin reservoir sand (8ms, ≈9.5m) in order to identify seismic edges, delimit and delineate subtle features, and finally compare the results obtained in time, frequency and quefrency and interpret. The results obtained from the conventional and developed techniques were applied on both standard (e.g. Kingdom Suite and Petrel program) and general interpretational platforms (e.g. Matlab, Pascal, Gnuplot and Surfer software) and found comparable but enhanced with the developed technique. They are presented as spectral and cepstral cross-plots, and maps (2D time slices). The newly developed transform algorithms and Computer program provided enhanced event perceptibility. The frequency tuning of the attributes of highly resolving transforms correlated with exact reservoir zones and detected seismic edges, subtle faults and channels. The practical relevance of this study is that field appraisal and clear identification of potential exploration projects and hydrocarbon fairways in particularly stratigraphic and geologically complex and fractured zones, etc. could be achieved using the developed technique and algorithms. This impacts on production and serves as baseline for the interpretation of similar geologic conditions in field data.

Keywords:- *Complex Cepstral Transform, Fourier Transform, Gamnitude, Quefrency, Saphe,*

I. INTRODUCTION

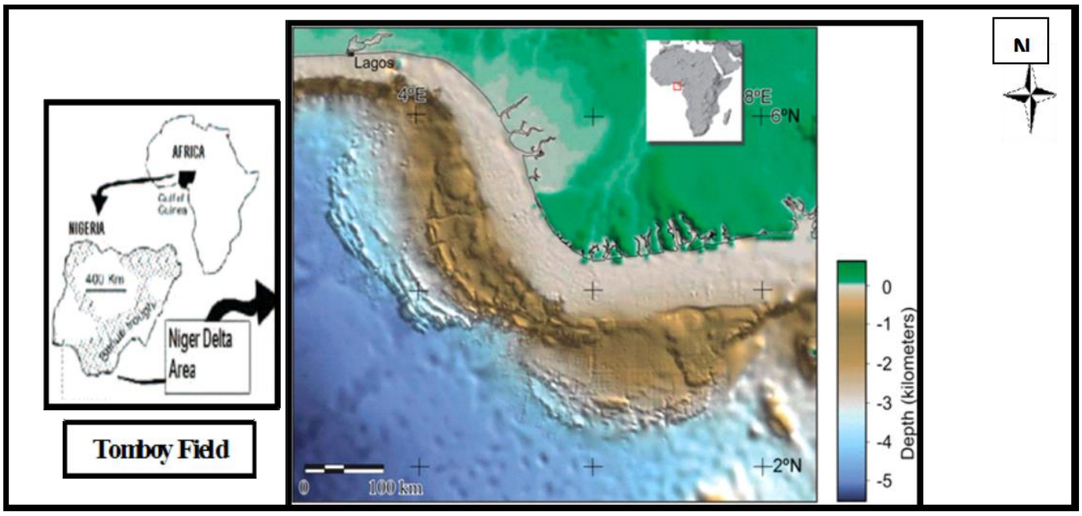
The seismic reflection method, ever since it was discovered, still remains one of the most effective tools in the imaging of subsurface geology and in the search for hydrocarbon bearing structures [1-3]. One of its' ultimate goal is to delineate structural and stratigraphic structures suitable for hydrocarbon accumulations. Seismic interpretation plays a vital role in the delineation of these hydrocarbon traps. It attempts to determine the geological significance of the seismic data. Originally, seismic reflection data was used to create maps that depict the geometry of the subsurface structures, thus, structural mapping or interpretation became prominent as many of the world's largest oil and gas fields were positioned on structural features that can easily be identified on seismic sections. With advancement in technologies, the use of seismic data has advanced to areas such as stratigraphic imaging and lithofacies prediction etc. These applications have led to the discovery of large scale oil and gas reserves trapped within subtle stratigraphic features. These subtle stratigraphic settings usually depict gradual and gentle configurations [4] that are not so obvious in conventional interpretation; thus, seismic exploration is not limited to structural features alone. Brown [5] reiterated the famous axiom that the 'easy oil and gas has been found, the more difficult oil and gas is to be found', and these thoughts have guided present objectives of oil exploration [5]. This has become more so as we forage into the ultra-deep waters, hostile environments, unconventional reservoirs, etc. with seemingly complex geology. Seismic stratigraphy provides the means to see these hidden or missed reservoirs that are often masked during conventional interpretation of seismic data. Stratigraphic traps are as important as structural traps but most often, are very subtle on seismic sections [6].

Seismic Stratigraphy is an important method in defining these hard to see "reservoirs". Cross and Lessenger [7], define seismic stratigraphy as the science of interpreting or modeling stratigraphy, sedimentary facies and geologic history from seismic data. Seismic stratigraphy aids in delineating those subtle stratigraphic features that are not so obvious in seismic sections and guides in the understanding of the depositional setting that aids the full appreciation of reservoir plays. Seismic data response carries information on rock properties. When properly transformed and processed, seismic attributes can be used to characterize hydrocarbon reservoirs both qualitatively and quantitatively [8]. With the most obvious structures already drilled, there is the present need to investigate smaller structures and stratigraphic traps often bypassed during routine standard seismic analysis.

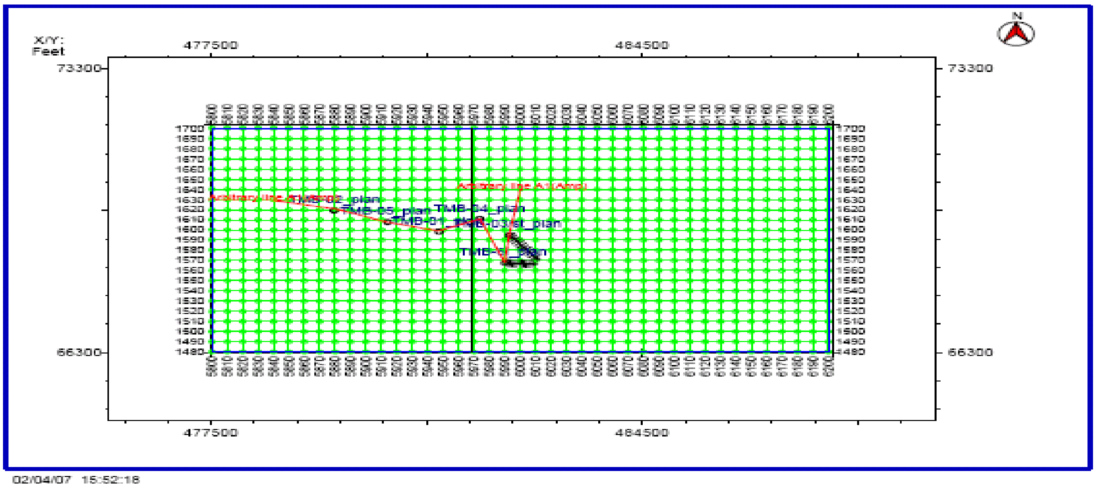
One very important approach in seismic stratigraphy is Spectral Decomposition (SD). It is a novel step in the interpretation workflow. Spectral Decomposition was originally pioneered through researches of British Petroleum (BP) and Amoco in the 1990s, spearheaded by [9]. It involves the analysis of seismic data in the frequency domain where spectral decomposition breaks the seismic data into its component frequencies. Analyzing seismic properties in the frequency domain aids in reservoir characterization [10]. The seismic data is transformed from time into the frequency domain where component frequencies are used to map temporal thickness, geological discontinuities, delineate stratigraphic settings such as channel sands and structural settings such complex fault systems [11]. The resultant images bring out the stratigraphic and / or structural features not readily apparent in the band limited 10-65Hz [12] seismic data.

Geologic Background

The data used for this study was acquired over ‘Tomboy Field’ in the Niger delta region (Figure 1). The region is a prolific hydrocarbon province formed during three depositional cycles from middle Cretaceous to Recent. It is located in Nigeria between latitudes 3^0N and 6^0N and longitudes $4^0 30^1$ E and 9^0E and bounded in the west by the Benin flank, in the east by the Calabar flank and in the north by the older tectonic elements e.g. Anambra basin, Abakaliki uplift and the Afikpo syncline. The basin is one of the largest subaerial basins in Africa. It has a subaerial area of about 75,000 km^2, a total area of 300,000 km^2, and a sediment fill of 500,000 km^3 [13]. In order of deposition, the Niger Delta is made up of three Formations (stratigraphy) which are: Akata Formation (compacted marine shale) and serves as the main source rock of the Niger delta; overlain by paralic or sand/shale deposits of Agbada Formation, which is the major oil and natural gas bearing facies in the basin. The paralic interval is overlain by a varying thickness of continental sands known as Benin Formation which contains no commercial hydrocarbons, although several minor oil and gas stringers are present [14-16]. Hydrocarbon is trapped in many different trap configurations. This implies that geological and geophysical analyses must be sophisticated, a departure from the conventional, in order to unmask hidden/by-passed reserves, usually stratigraphic and laden with huge hydrocarbon accumulation.



(a) Tomboy Field, Niger Delta (Short and Stauble [17], as cited in [18]).



(b) Tomboy Field, Niger Delta: Base map of survey area showing the arbitrary line (in Red) in the field.

Figure 1: (a) Tomboy Field, Niger Delta, showing the Bathymetric Sea-floor image of the Niger Delta (b) Base map of survey area showing the arbitrary line (in Red). The well under consideration is TMB 06.

II. THEORY OF SIGNAL TRANSFORMS

2.1 Fourier Transform

Fourier analysis splits a signal or waveform into its sinusoidal components based on the assertion that the frequency is not changing with time (stationary). Fourier transform allows insights of average properties of a reasonably large portion of trace but it does not ordinarily permit examination of local variations [19]. In practice, the standard algorithm used in digital computers for the implementation of Fourier transform is the Fast Fourier Transform (FFT/DFT).

2.2 Discrete Fourier Transform (DFT)

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

$$f(w) = \sum_{t=-\infty}^{w-\infty} f(t) \exp(-iwt) \qquad (1)$$

and the inverse discrete Fourier transform is

$$f(t) = \sum_{t=-\infty}^{w-\infty} f(w) \exp(iwt) \qquad (2)$$

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’. Also, F(w) comprises both real ($F_r(w)$ and imaginary $F_i(w)$ components.

Hence

$$F(w) = F_r(w) + iF_i(w) \qquad (3)$$

$$A(w) = [F_r^2(w) + F_i^2(w)]^{1/2} \qquad (4)$$

$$\phi(w) = \tan^{-1}\left[\frac{F_i(w)}{F_r(w)}\right] \qquad (5)$$

where A (w) and ϕ (w) are the amplitude and phase spectra respectively (Yilmaz, 2003).

2. 3 Cepstral Transform (CT)

Cepstral decomposition is a new approach stated by [20] that extends the widely used process of spectral decomposition. It is capable of measuring bed thickness even when the bed itself cannot be interpreted. The Cepstrum processing technique gives a solution of other signals which have been convolved in time domain because the operation of the non-linear mapping can be processed by the generalized linear system (Homomorphic system) [21]. Cepstral analysis is a special case of Homomorphic filtering. Homomorphic filtering is a generalized technique involving (a) a nonlinear mapping to a different domain where (b) linear filters are applied, followed by (c) mapping back to the original domain. The independent variable of the Cepstrum is nominally time though not in the sense of a signal in the time domain , and of a Cepstral graph is called the Quefrency but it is interpreted as a frequency since we are treating the log spectrum as a waveform. To emphasize this interchanging of domains, Bogert et al., [22], coined the term Cepstrum by swapping the order of the letters in the word Spectrum. The name of the independent variable of the Cepstrum is known as a Quefrency, and the linear filtering operation is known as Liftering. The Cepstrum is useful because it separates source and filter and can be applied to detect local periodicity. There is a complex Cepstrum [23] and a real Cepstrum. In the “real Cepstrum”, as opposed to the complex Cepstrum used here, only the log amplitude of a spectrum is used [20]. Complex Cepstrum uses the information of both the magnitude and phase spectra from the observed signal. The complex Cepstrum method is used to retrieve signals generated by a convolution process and has been called Homomorphic deconvolution [23].

Various authors have given several definitions of the CT. Oppenheim & Schafer [24], defines CT as the Fourier transform (FT) of the log of the spectrum of a time domain signal. Sajid & Ghosh [25], defines the CT as the Inverse Fourier transform (IFT) of the log of the magnitude of the Fourier transform of the signal. The definition by [25] is the definition most employed in speech analysis and homomorphic deconvolution. [20], defines the CT as the Fourier transform of the natural logarithm of the Fourier Transform of the signal. The various definitions of the CT are as follows:

(i) (FT(log (FT (Signal)))) – Hormorphic deconvolution (6)
(ii) (FT (ln (FT (Signal)))) – Seismic Interpretation (7)
(iii) (FT (FT (Signal))) – pseudo-cepstrum (8)

The applications can be found from seismic signal, speech and imaging processing. Kepstrum was named by [26], and used in seismic signal analysis, although the literature on its application is limited. The Kepstrum and complex Cepstrum give almost same results for most purpose.

The Cepstrum can be defined as the Fourier transform of the log of the spectrum. Given a noise free trace in time (t) domain as x (t) obtained by convolution of a wavelet w(t) and reflectivity series r(t) and assuming X (f), W (f) and R (f) are their frequency domain equivalents, then ,Since the Fourier transform is a linear operation, the Cepstrum is

$$F[\ln(\mathrm{mod}\ X)] = F[\ln(\mathrm{mod}\ W) + F[\ln(\mathrm{mod}\ R)] \qquad (9)$$

To distinguish this new domain from time, to which it is dimensionally equivalent, several new terms were coined. For instance, frequency is transformed to Quefrency, Magnitude to Gamnitude, Phase to Saphe, Filtering to Liftering, even Analysis to Alanysis. Only Cepstrum and Quefrency are in widespread today, though liftering is popular in some fields [20].

III. METHOD

3.1 Field Data

The 3D seismic and well data used in this study were obtained over 'Tomboy Field' by Chevron Corporation Nigeria. It consists of a base map, a suite of logs from six (6) wells. Some of the log types provided are Gamma-Ray (GR), Self-Potential (SP), Resistivity, Density, Sonic, etc. Lithologic logs (GR) and (SP) were first plotted to identify the hydrocarbon window of interest and then correlated with Resistivity logs. This Interval corresponds to 2648-2672 milliseconds using time-depth conversion.

3.1.1 Well-Log Analysis

Definition of Reservoir (Thin-Sand A) Interval

The field under investigation has six drilled wells. The sand intervals were identified on the basis of characteristic signature response of lithologic logs, namely, GR, to lithofacies type, i:e a high for GR log deflection in the presence of shale facies, and a low in the presence of sand facies. In addition, high resistivity log signature also points to possible presence of hydrocarbon**.** The results are displayed as Figures 2 (a-b) to Figures 3 (a-b). While each of the displays is self-explanatory, the summary of the analysis is given in sub-sub-section

Concepts in Spectral and Cepstral Analysis

In seismic attribute analysis, amplitude or magnitude (envelope) indicates local concentration of energy, bright spots, gas accumulation, sequence boundaries, unconformities, major changes in lithology, thin bed tuning effects, etc; phase measures lateral continuity/discontinuity/edge) or faulting, showing clear imaging of bedding configuration and has no amplitude information. In the case of the phase attribute, there is a flip owing to sign reversal [27]. The frequency attribute reflects attenuation spots, indicates hydrocarbon presence by its low frequency response, reveals edges of low impedance thin beds, fracture zone indication-appears as low frequency zones, and also indicates bed thickness. Higher frequencies indicate sharp interfaces or thin shale bedding, lower frequencies indicate sand rich beds, sand/shale ratio indicator [28]. In Cepstral domain, the Gamnitude, Saphe and Quefrency are interpreted in a similar manner to Magnitude, Phase and Frequency in the Spectral domain. Saphe highlights discontinuity/edge and lithologic changes, while Quefrency indicates fracture zone, hydrocarbon presence by its low values.

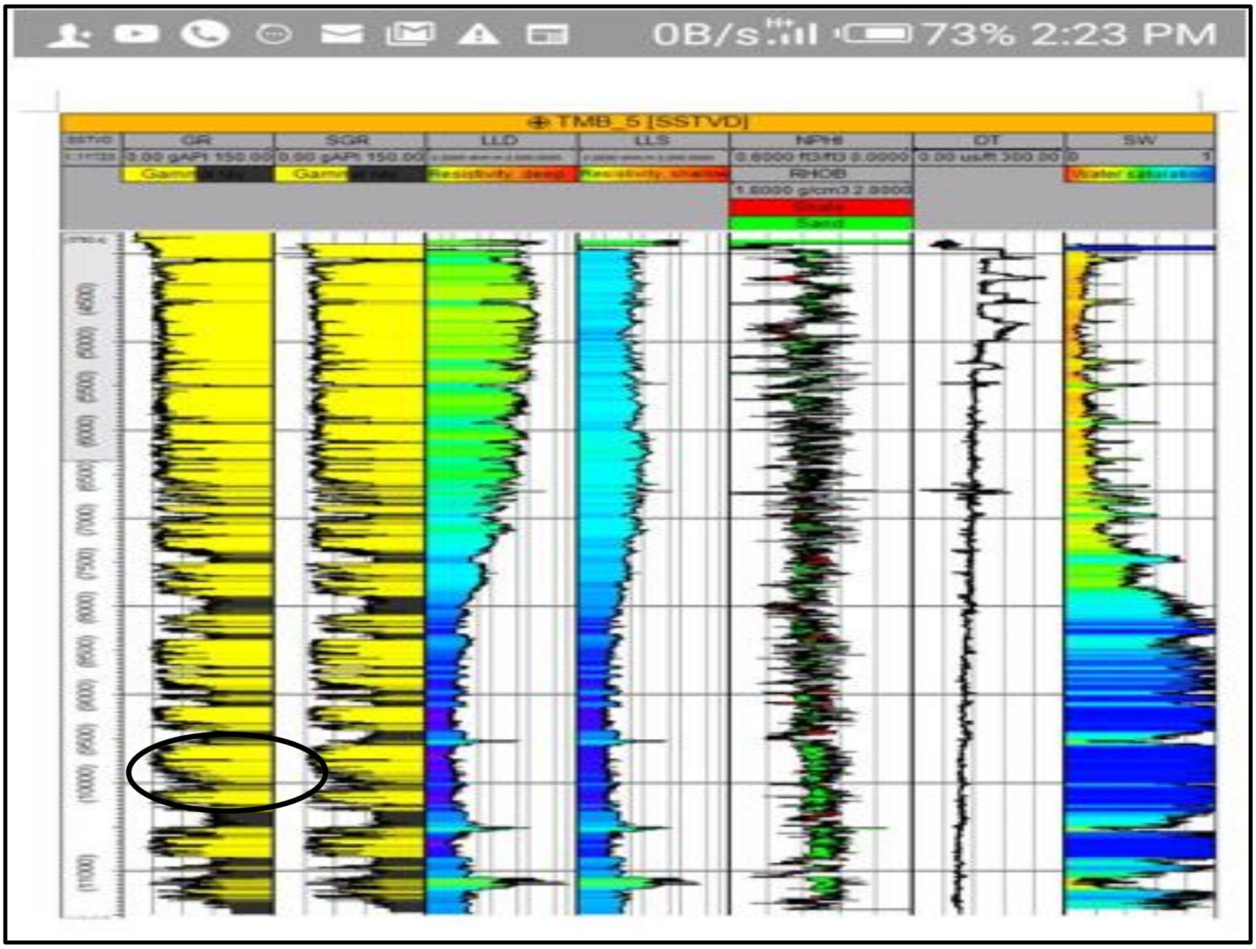


Figure 2a: Gamma ray, Resistivity and Sonic logs for total measured depth 3000ft – 12000ft of **Well 05** with suspected and preferred sand interval identified. (Petrel Software).

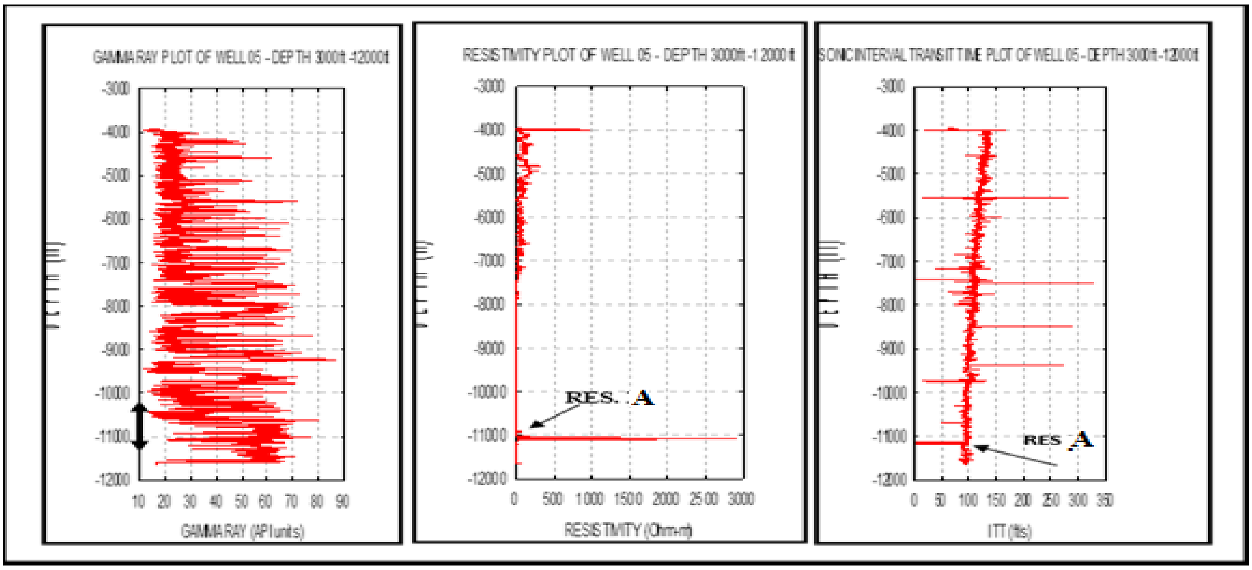


Figure: 2b Gamma ray, Resistivity and Sonic logs for total measured depth 3000ft – 12000ft of **Well 05** with suspected and preferred sand interval identified. (Gnuplot Software).

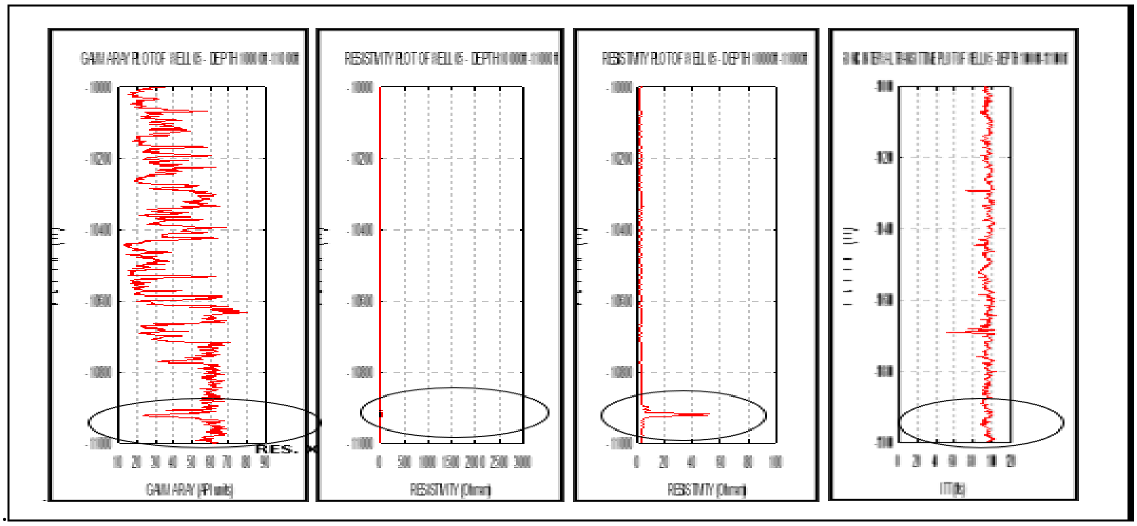


Figure 3a: Identified Thin Sand Interval Enhancement by Scale Adjustment.

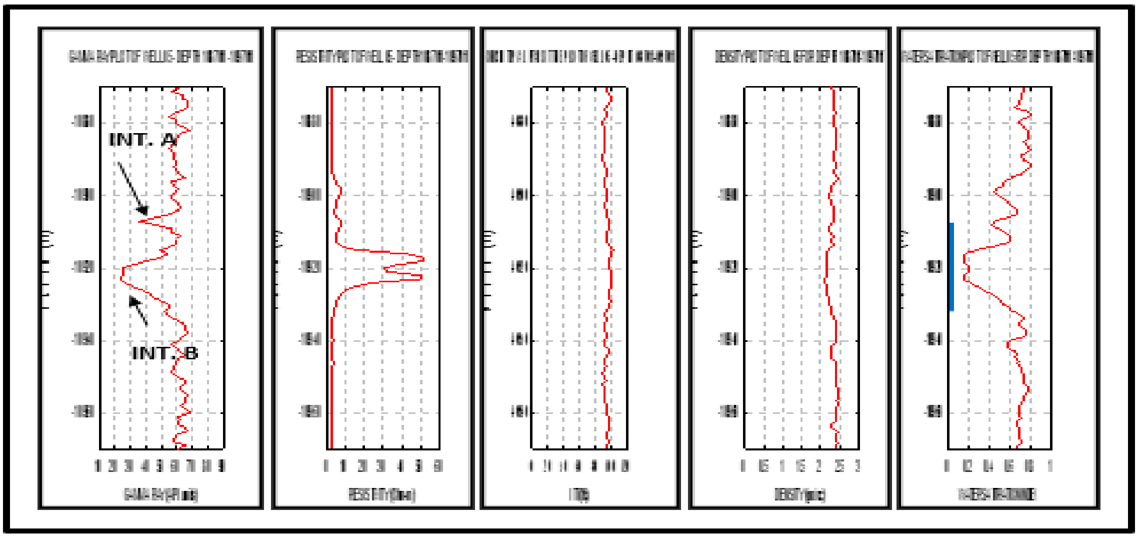
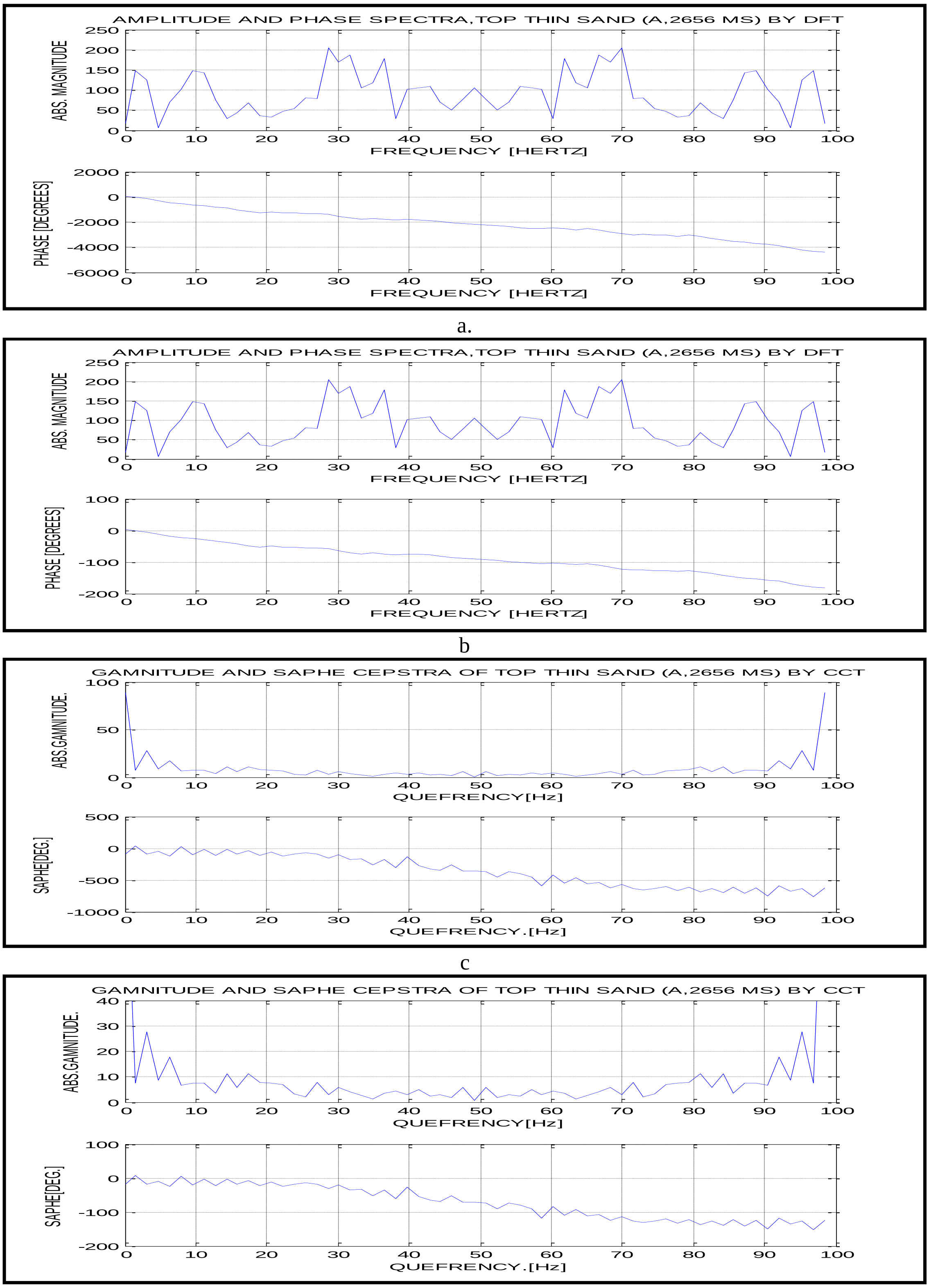


Figure 3b: Reservoir A is thinly bedded and comprises two peaks, A and B. The interval has low Gamma ray,high Resistivity, relatively high Sonic values and low water saturation. (Sand Interval Enhancement by Scale Adjustment).

3.1.2 Application to Seismic Amplitude Data of Target Reservoir, A, about (8ms, ~9.5m)

The results obtained are displayed as Figures 2-10. After identifying the target reservoir sand and it effective top and base, its top (at 2656 ms.) was then spectrally and cepstrally decomposed using DFT and CCT. Therefore the results shown are for the top sand only.

IV. RESULTS AND DISCUSSION



a.

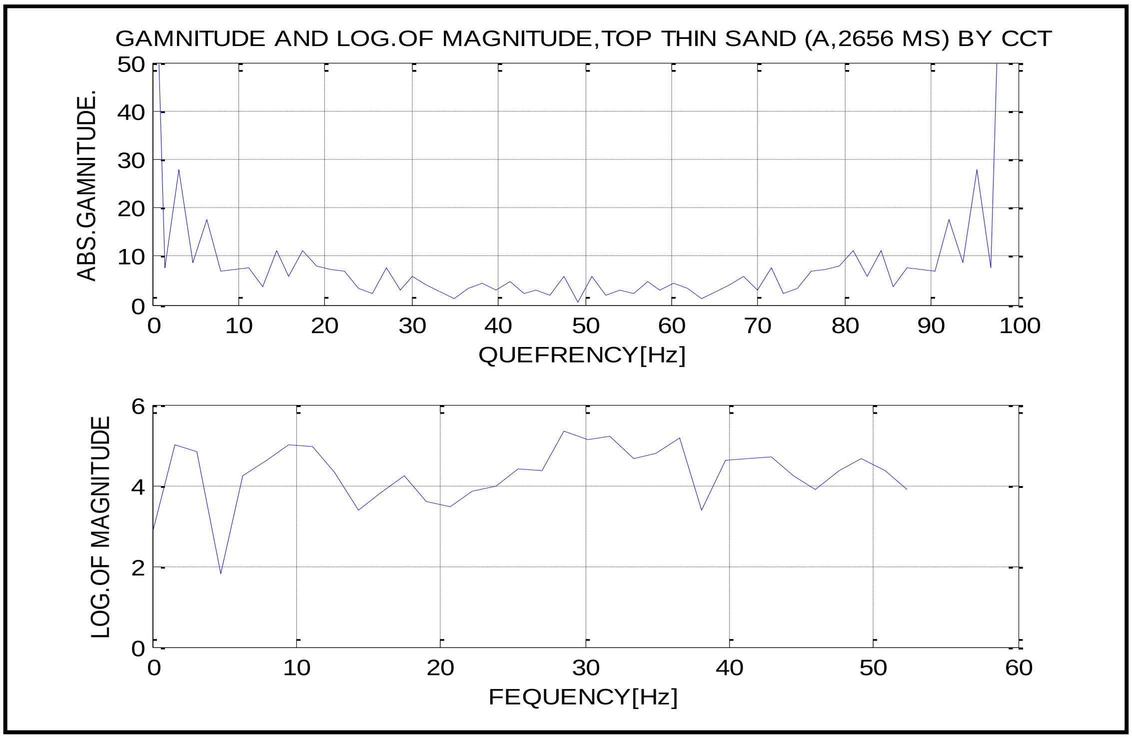
b

c

d)

Figure 4: **Tomboy Field, Niger Delta:** Comparison of Amplitude range and Frequency recoverable by DFT and CCT.CCT is more resolving

Logarithmic Plots



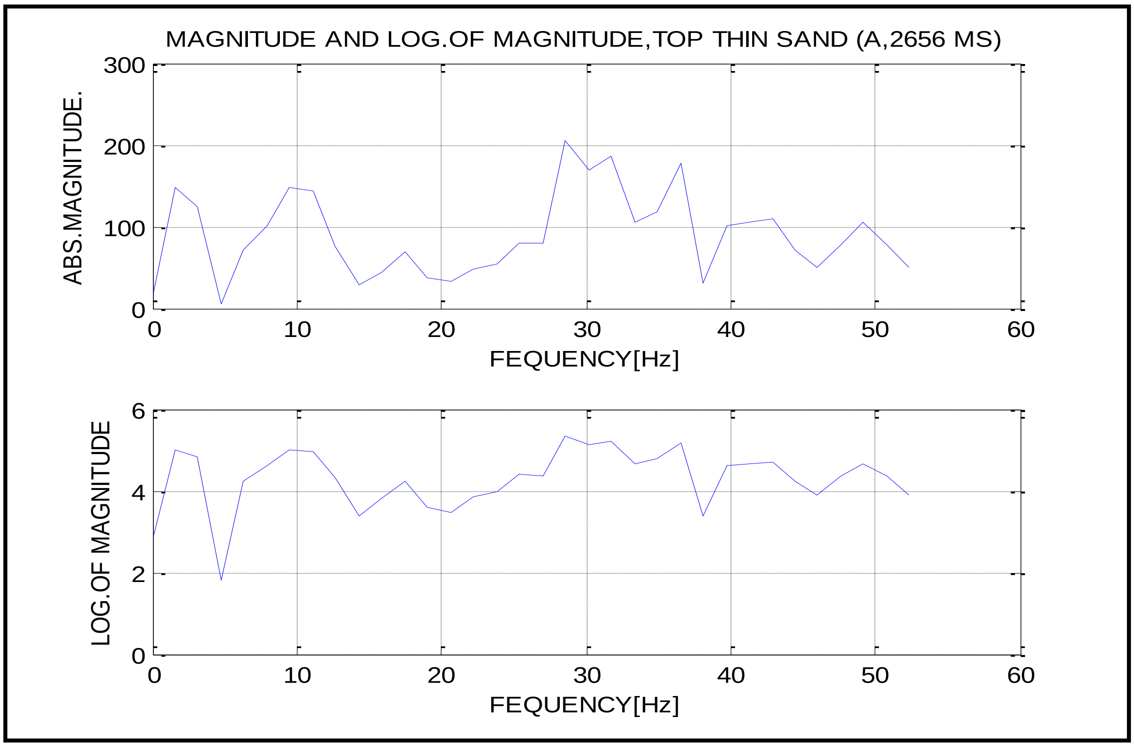


Figure 5: **Tomboy Field, Niger Delta: Reservoir A (Top Sand, 2656 ms):** Logarithmic. Here more frequency recovery and low amplitude values(subtle/stratigraphic events) can be seen in CCT than in DFT. (See scales).Observe the periodicity of both spectra, and the re-scaled nature of the log magnitude spectrum.

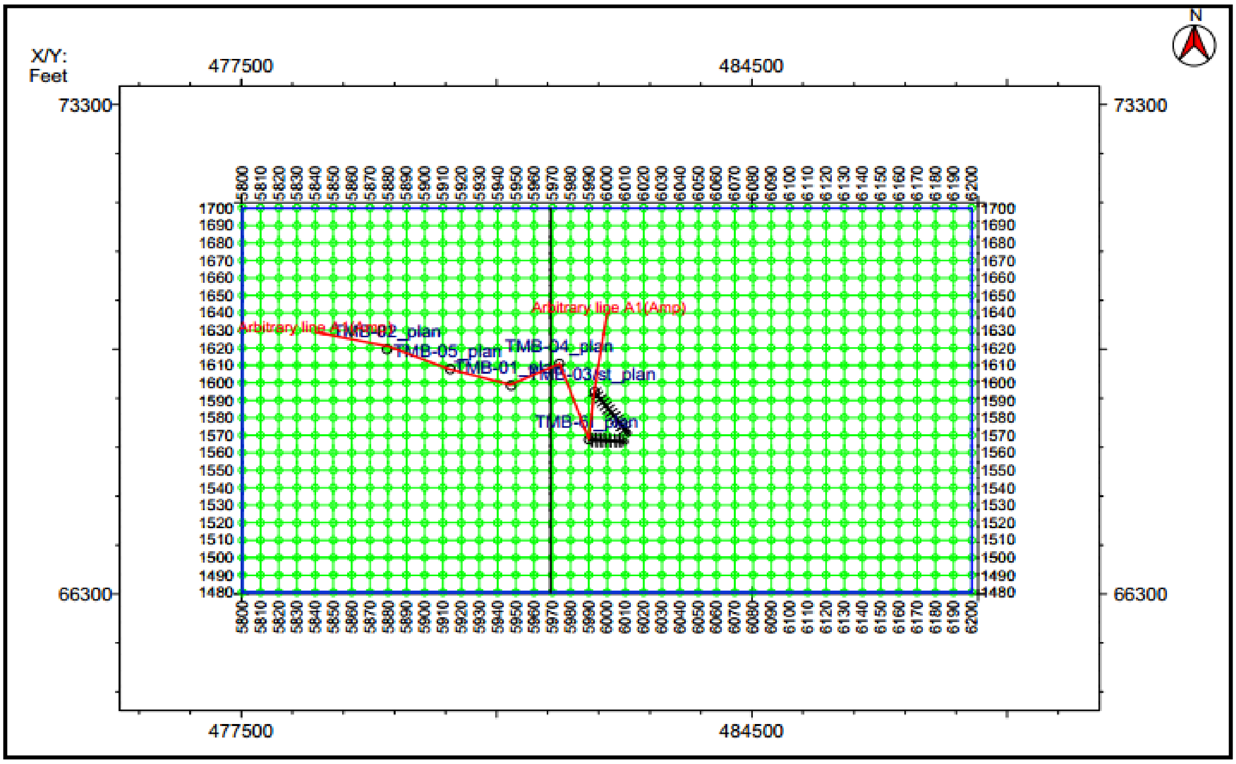


Figure 6: Base map showing the arbitrary line (in Red). The Arbitrary line connects the entire six wells (black dots). The wells under consideration are TMB 05 & TMB 06.

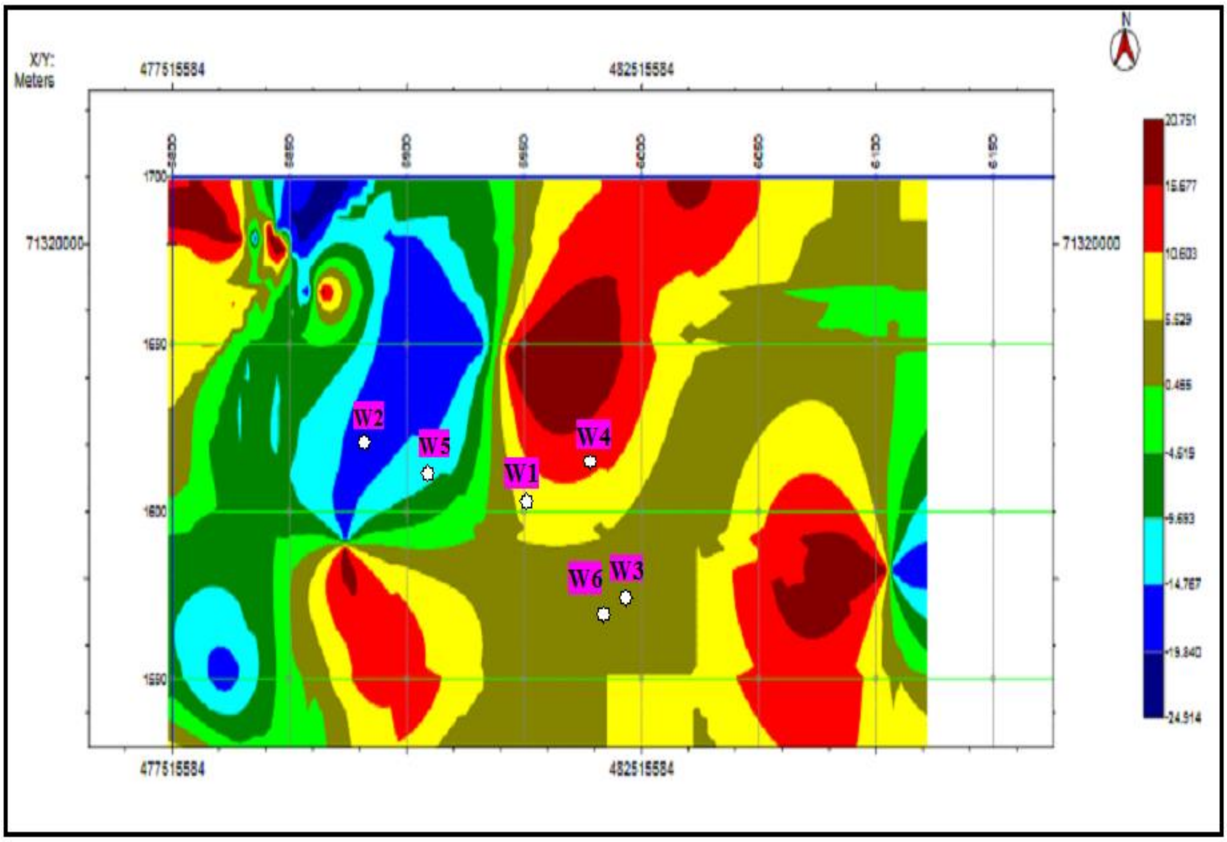
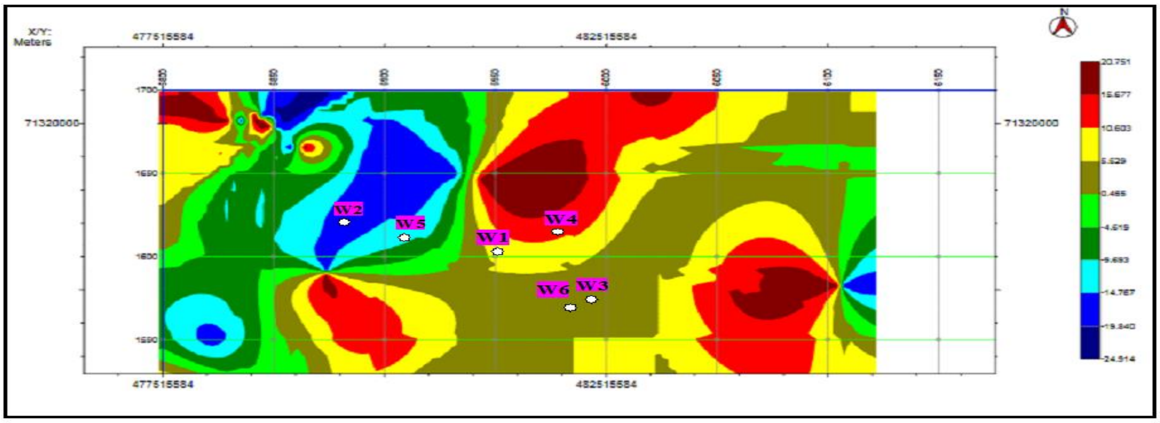
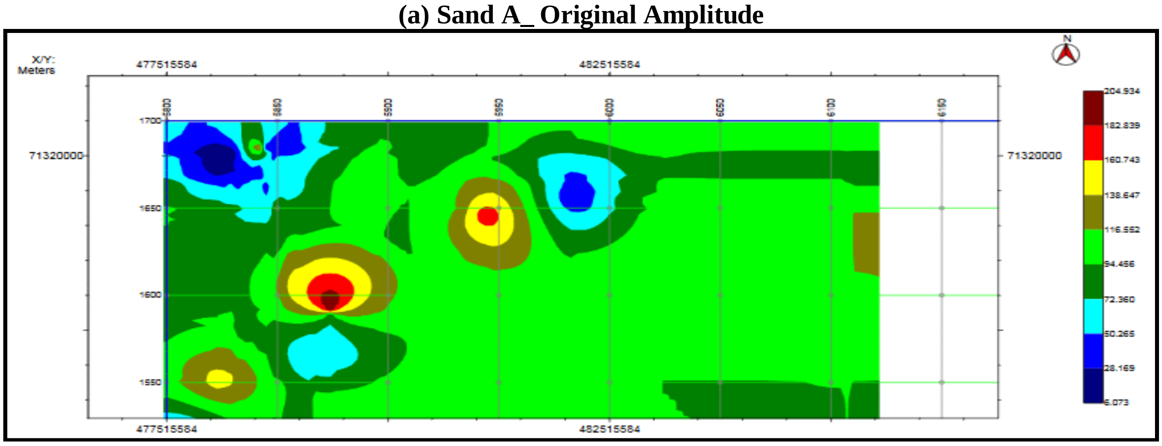


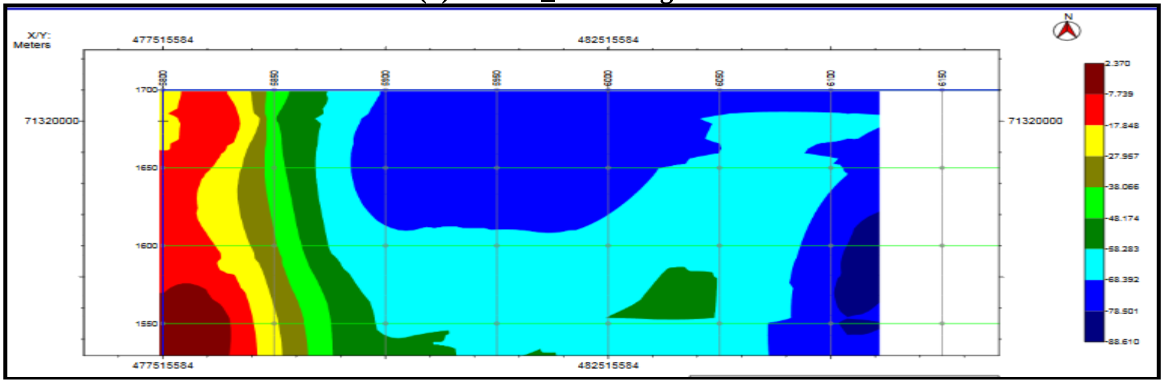
Figure 7: **Tomboy Field, Niger Delta: Reservoir A (Top Sand, 2656 ms):** Original **Amplitude** map showing the drilled well locations.



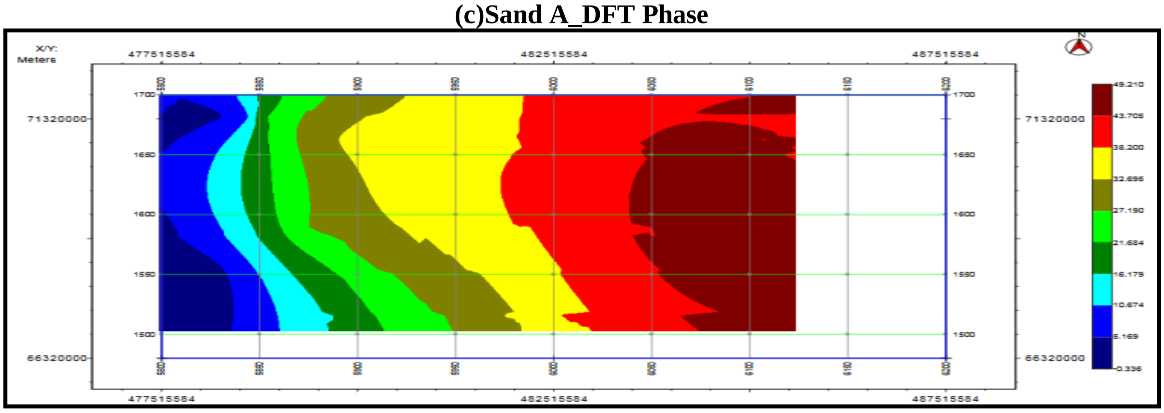
(a) Sand A_ Original Amplitude



(b) Sand A_ DFT Magnitude

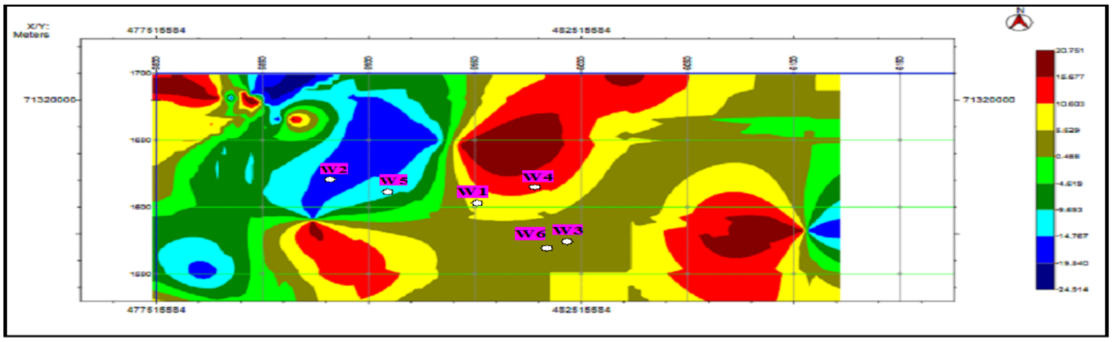


(c)Sand A_DFT Phase

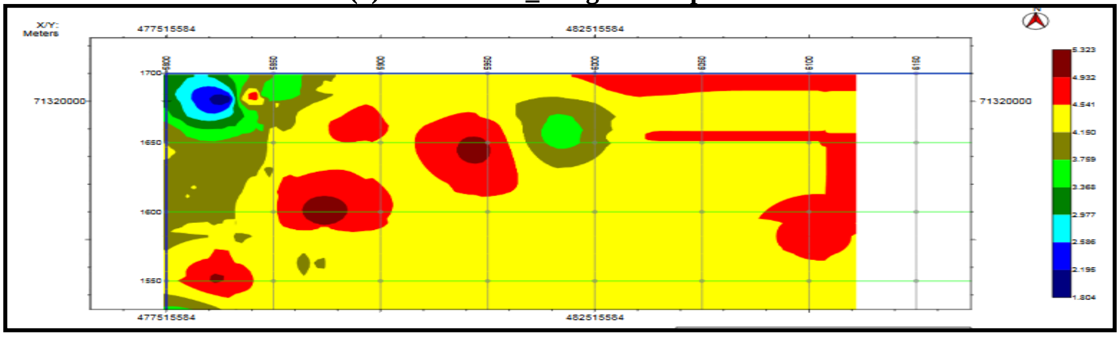


(d) Sand A_DFT Frequency

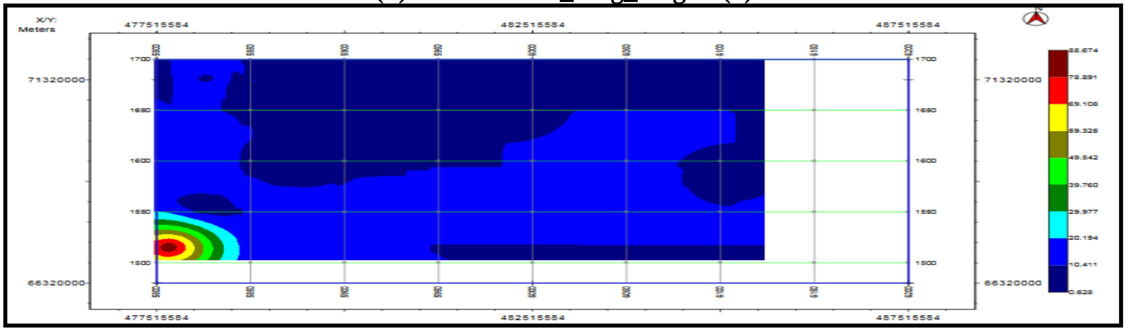
Figure 8: **Tomboy Field, Niger Delta: Reservoir_ A (Top Sand, 2656 ms):** Computed Discrete Fourier Transform (DFT) Attributes



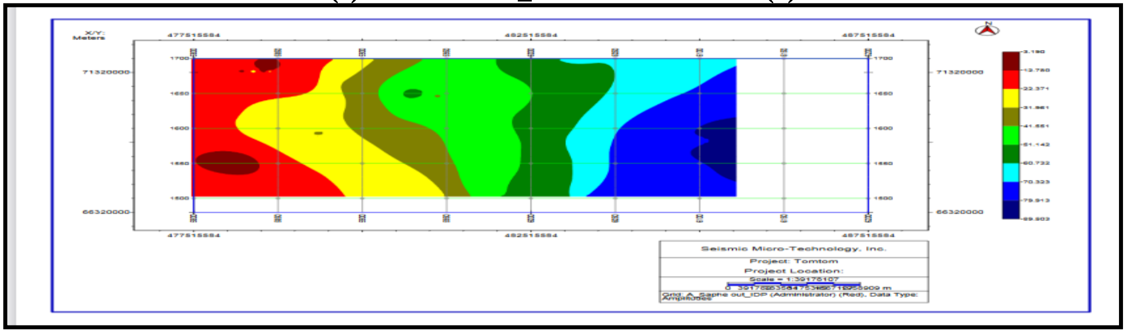
(a)Thin Sand A_ Original Amplitude



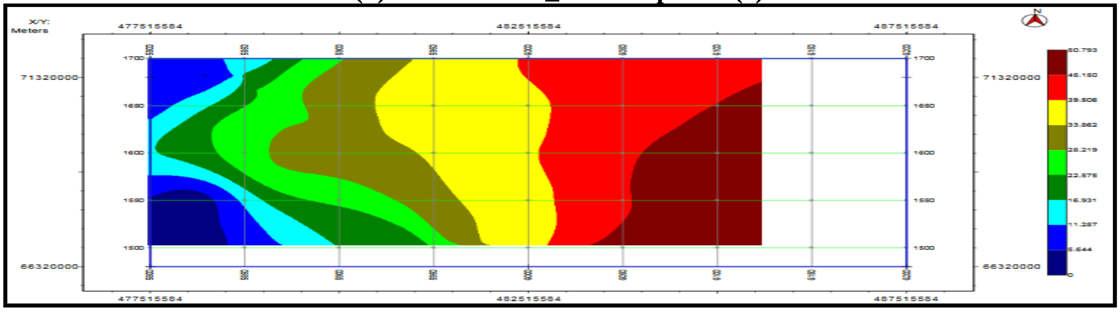
(b) Thin Sand A_ Log_mag of (a)



(c) Thin Sand A _ CCT Gamnitude of (a)



(d) Thin Sand A _ CCT Saphe of (a)



(e) Thin Sand A _ CCT Quefrency of (a)

Figure 9: **Tomboy Field, Niger Delta: Reservoir_ A (Top Sand, 2656 ms):** Computed Complex Cepstral Transform (CCT) Attributes.

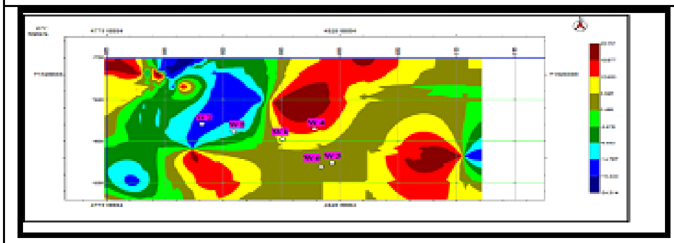
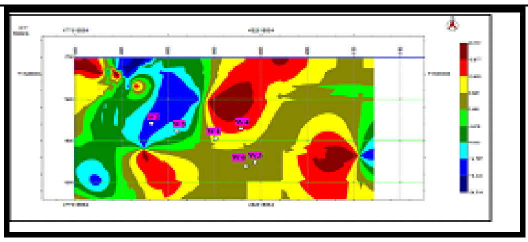
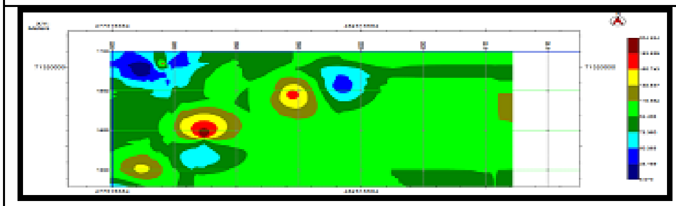
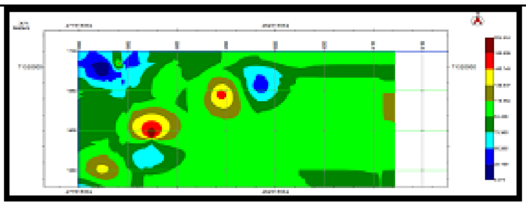
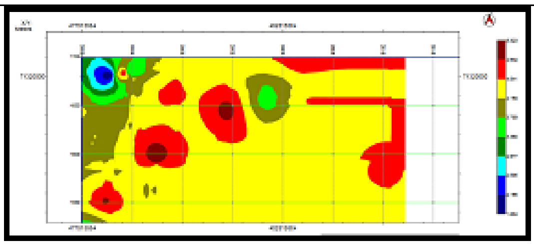
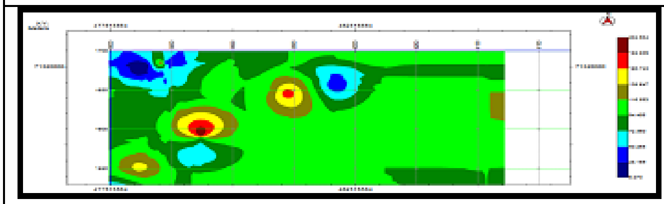
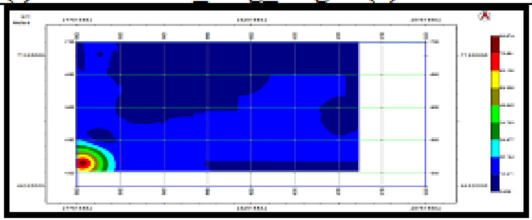
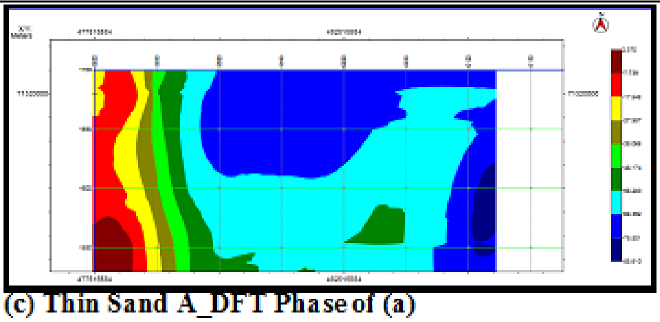
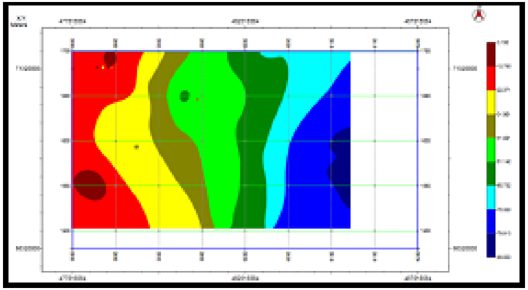
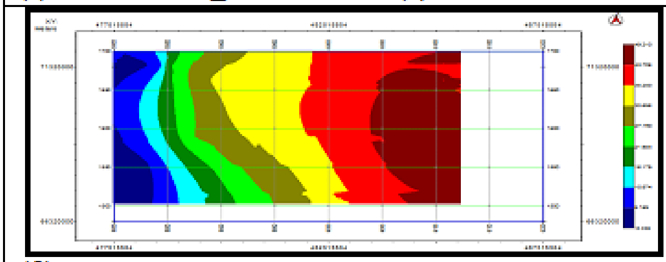
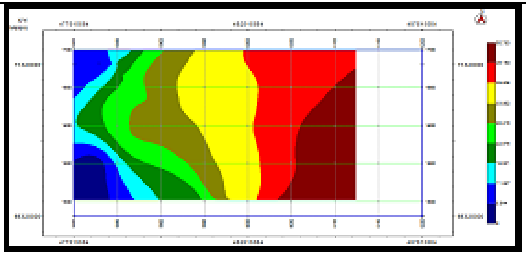
DFT RESULTS	CCT RESULTS
 **(a)Thin Sand A_ Original Amplitude**	 **(a/e)Thin Sand A_ Original Amplitude**
 **(b) Thin Sand A_ DFT Magnitude of (a)**	 **(b) Thin Sand A_ DFT Magnitude of (a)**
NO SIMILARITY	 **(f) Thin Sand A_ Log mag of (a)**
 **(b) Thin Sand A_ DFT Magnitude of (a)**	 **(g) Thin Sand A _ CCT Gamnitude of (a)**
 **(c) Thin Sand A_DFT Phase of (a)**	 **(h) Thin Sand A _ CCT Saphe of (a)**
 **(d) Sand A_DFT Frequency of (a)**	 **(i) Thin Sand A _CCT Quefrency of (a)**

Figure 10: **Tomboy Field, Niger Delta: Reservoir A (Top Sand, 2656 ms): Comparison of DFT and CCT Attributes Maps.** The Re-scaled nature of the log magnitude spectrum results in a more linear and clearer image (Non- linear system becoming more linear). Note the wider Quefrency range of the Cepstrum than Frequency range of the Spectrum. CCT attributes in Figures 10 (a, b, f, g, h, i) are clearer and more symmetrical than their DFT equivalents in Figures 10 (a, b, c, d).

4.1 Results

Figures 7, 8 and 9, show the original amplitude map, spectral decomposition by DFT, and cepstral decomposition by CCT respectively. While Figure 10 displays the summary. In Figure 10, a comparative display of results of spectral decomposition technique by DFT and its extension, the cepstral decomposition technique by CCT, and their resolution capabilities are examined. By definition, a thin bed is a geologic layer whose thickness is less than one-fourth of the length of the dominant wavelength in the seismic wave field, which can be 200ft to 300 ft (~65 m to 100 m); therefore, many thin beds have thicknesses of 50ft to 75 ft (~15m to 22 m) and many reservoirs are less than 18.2m (60ft) thick on the average. This is generally sub-seismic resolution and can therefore not be resolved in a conventional seismic image. The thin bed under consideration, Reservoir A (8 ms, approximately 9.5m) is not discernible or evident on normal seismic image as explained above .Although the thin bed was identified on well log (large bandwidth (, i.e. from 0-1000Hz and greater) by successive plotting and zooming at short depth intervals, it could not be identified on the seismic trace since it is band limited (5-65 Hz). Therefore interpretation of this bed can only be done field wide from seismic amplitude using high resolution techniques such as applied here. This is a key merit of this study. In Figure 10, the low frequency values represent the sand zones (actual well zone coincide with the yellow area and left of it, while high frequency values represent thin shale bedding). The intermediate frequencies are the sand/shale regimes. This implies that for field development, drilling direction should be to the west. Most of the drilled wells of good quality are between yellow and light blue zones. Deep blue zone is undeveloped. The wells of poor data quality (or dry) are in the red and brown zones (extreme right). Besides, Gamnitude shows the sequence boundaries, Saphe shows discontinuity, while Quefrency indicates shows hydrocarbon presence by its low values.

4.2 Discussion

In this discussion, Cepstrum analysis applied to target thin sand reservoir (8 ms, 9.5m), is a form of spectral analysis where the output is the Fourier transform of the log of the magnitude spectrum of the input waveform. This is an attempt to make a non-linear system more linear. Naturally occurring partials (lowest frequency component in signal) in a frequency spectrum are often slightly inharmonic (not harmonic), and the cepstrum attempts to mediate this effect by using the log spectrum**.** The only variable affecting resolution, which can be controlled, is the frequency. Low frequency information below 10Hz associated with stratigraphy and high frequencies greater than 100 Hz in well data which are vital for detailed interpretation, are absent from the seismic trace. Hence the need for the development of an improved technique. The DFT frequency range is- -0.3Hz to 49.2Hz with effective range of -0.3Hz to 38.2Hz and Inharmonic while that of CCT is also 0.0Hz to 50.8Hz with effective range of 0.0Hz to 39.5Hz but with improved linearity. The normalized DFT Phase range is – $88.6.0^0$ to $+2.37^0$ while the normalized CCT Saphe range is – 48.9^0 to -2.9^0 with better lithofacies segmentation. Note that precise linearity facilitates identification of hypocenter of reservoir and hence proper Rig placement at its epicenter. Aside normal applications, this study is particularly applicable in areas of uncertainty in data and time such as in complex geologic environments as in marginal fields, etc. Several of such marginal fields (Undeveloped) located onshore and in the shallow waters exist in Nigeria and elsewhere.

V. CONCLUSIONS

An investigation into a new technique, algorithm and computer program using state of the art techniques and highly efficient seismic compatible, and invertible mathematical transforms for unmasking hidden/ very subtle/thin stratigraphic traps in the interpretation of 3D seismic data obtained from Niger Delta has been undertaken. Such hydrocarbon traps contain huge accumulations and are generally bypassed in favourable and particularly unfavourable or complex geologic environments. The aim of this study was to develop a unique, high resolution and optimal technique for mapping stratigraphy which is not seen after normal data interpretation on commercial interpretation platforms using highly resolving signal transforms. The key objectives were to: build efficient workflow algorithms and computer program codes from basics (mathematical functions) for spectral decomposition including each of its extensions using the Discrete Fourier Transform (DFT), Complex Cepstral Transform (CCT) and apply it to a very thin sand (~8ms thin, 9.5m target reservoir) along measured seismic line in order to identify seismic edges, delimit and delineate subtle features, and finally compare the results obtained in time, frequency and quefrency domains and interpret. The results obtained from the conventional and developed techniques were implemented on both standard and general interpretation programs and found comparable and enhanced with the developed technique. They are presented as spectral and cepstral cross-plots and maps. The newly developed transform algorithms and Computer program provided enhanced event perceptibility. The frequency tuning of the attributes of highly resolving transforms correlated with exact reservoir zones and detected seismic edges, subtle faults, channels, etc. The practical relevance of this study is to facilitate field appraisal, clear identification of potential exploration projects and hydrocarbon fairways in particularly stratigraphic and geologically complex reservoir targets, such as marginal fields etc. This impacts on production and serves as basis for the interpretation of similar geologic situations in field data. It is recommended that higher and more resolving seismic compatible and invertible transforms be applied for better event visibility in future .This will also enhance the availability of the very limited literature in this area of specialization.

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