Opportunity Generation in Mature Field Settings using Spectral Decomposition: Niger Delta Field Examples

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ABSTRACT

The current operating environment, arising from volatile oil prices, challenges the industry to be proactive with cost saving innovations and application of cutting-edge technology. Spectral decomposition technology (SDT) is a proven method for enhancing opportunity generation and optimizing well placement through better imaging of subtle structural and stratigraphic features. Three case studies of SDT integration for drill well opportunity generation in mature field settings offshore Niger Delta are presented. In all cases, SDT allowed us to discriminate the most significant frequency components and optimize seismic data for structural and stratigraphic interpretation. Deepwater examples are taken from two fields where SDT was used to delineate thin-beds that fall at or below seismic resolution. SDT enhanced stratigraphic details that were not obvious in traditional amplitude extractions. Results were used for improved Environment of Deposition (EOD) definition, reservoir connectivity and well placement optimization. In the shallow water environment example, SDT was used to enhance regional mapping of fluid contacts (flat events) in a shallow water field. Frequency volumes aided mapping of gas-oil-contact (GOC) and oil-water-contact (OWC) at locations where they were less visible on traditional stacked time-domain seismic volumes. Results were successfully used as part of field-wide review to assess future opportunities in the field. In some of the cases, additional deeper and shallower anomalies were identified, which could be subjects of future investigations. The technology is currently being used to support other ongoing projects in shallow JV and Deepwater fields.

INTRODUCTION

SDT is an important analysis tool that is used to decompose seismic signal into its constituent frequencies. This allows the interpreter to see amplitude and phase tuned to specific wavelengths, just as a radio can pick out a single station, or prism a single color (Hall and Trouillot, 2004). SDT decomposes the seismic data into individual frequency components that fall within the measured seismic bandwidth, so that the same subsurface can be viewed at different frequencies (Partyka et al., 1999). Because stratigraphy resonates at wavelengths dependent on the bedding thickness, thin beds or features will be tuned and have relatively higher amplitude at higher frequencies (McArdle and Ackers, 2012).

SDT has been employed in seismic interpretation over the past decades and has become a well-established tool that helps in the analysis of subtle structural and stratigraphic features. Partyka et al. (1999) introduced SDT as an interpretation technique and presented an interpretation workflow that was successfully used for imaging and mapping of temporal bed thickness and geologic discontinuities in 3D seismic data. Since then, spectral decomposition has been widely used in seismic data interpretation in applications such as stratigraphic and complex fault system characterization (Marforth and Kirlin, 2001; Wei, 2010), quantitative reservoir characterization (Hall and Trouillot, 2004; McArdle and Ackers, 2012), gas identification (Burnett et al, 2003; Odebeatu et al., 2006), and direct hydrocarbon detection (Yoon and Farfour, 2012). In all cases, SDT is shown to be a robust tool to enhance structural and stratigraphic interpretation.

In this paper, we present three case studies of SDT integration for opportunity generation in mature field settings offshore Niger Delta. In all cases, SDT allowed us to generate frequency volumes to view and extract new information from seismic data. In the deepwater examples, SDT was applied for channel system delineation. This has improved our understanding of reservoir architecture and connectivity, as well as Environment of Deposition (EOD). In the shallow water example, SDT was used to aid field-wide mapping of flat events associated with GOC and OWC. This provided improved confidence and accuracy in the mapping of seismic flat events, and ultimately, in the field-wide evaluation of future opportunities in the field.

In the following sections, we present a brief overview of theoretical concepts and explain the choice of SDT methods that were used in this study. Next, we discussed the field examples; highlighting technical impacts of the SDT integration. Finally, we summarize various learnings with recommendations for improved SDT integration into future opportunity generation studies in shallow JV and deepwater fields in Niger Delta and beyond.

THEORETICAL CONCEPTS AND METHODS

An important underlying principle in SDT is the Fourier transform. In general, a seismic trace $g(t)$can be formulated as (Bracewell, 1986; Zhang et al., 2005):

$$g(t) = \int a(t,f)e^{i\emptyset(t,f)}\,df \qquad (1)$$

where$a(t,f)$and $\emptyset(t,f)$are amplitude and phase components, respectively, at time t and frequency f. The Fourier transform $G(f)$ of the seismic trace $g(t)$ is the inner product of the signal with the basis function $e^{i\omega t}$(Bracewell, 1986; Sinha et al. 2005):

$$G(f) = \{g(t), e^{i\omega t}\} = \int_{-\infty}^{\infty} g(t)e^{-i\omega t}dt \qquad (2)$$

where $\omega = 2\pi f t$. A seismic signal when transformed into frequency domain using the Fourier transform (Equation 2), gives the overall frequency behavior, in a stationary sense, over a large window representing entire spectrum of the signal (Bracewell, 1986). For spectral decomposition, the signal is 'windowed' (that is a short segment of the signal is taken) and Fourier transform is performed on the windowed data to obtain local frequency information. In other words, a window or kernel function (a filter) is introduced into Equation 2 such that (Sinha et al. 2005):

$$G(f,\tau) = \{g(t), s(\tau)e^{iwt}\} = \int_{\infty}^{\infty} g(t)\bar{s}(t,\tau)e^{-i\omega t}dt \qquad (3)$$

where$G(f,\tau)$ is a spectrally decomposed signal at analysis window$s(t,\tau)$ (where τ is a window's parameter with $\bar{s}$(t,τ) being complex conjugate). Generally, different direct and analogous approaches have been proposed and applied to solve Equation 3 and its various adaptations. This has given rise to varieties of spectral decomposition methods for seismic data interpretation. Examples of these methods include: short time Fourier transform (STFT) (Partyka et al. 1999); continuous wavelet transform CWT (Sinha et al., 2005); the S-transform (Stockwell et al., 1996; Odebeatu et al., 2006); constrained least-squares spectral analysis (CLSSA) (Puryear et al., 2012); Gabor transforms (Ying-Pin et al., 2013); and matching pursuit spectral decomposition (Mallat and Zhang, 1993; Wang, 2007); among others. A comprehensive review of various spectral decomposition techniques is presented by Tary et al. (2014).

According to Castagna and Sun (2006), SDT can be categorized as 'useful' or 'not useful' for the specific applications, and not as 'right' or 'wrong'. All the techniques have characteristics merit or demerit and different techniques are required or could be more suitable for different applications (Chakraborty and Okaya, 1995). Generally, successful applications of each of these methods for structural and stratigraphic interpretations have been documented (for examples: Partyka et al. 1999; Hall and Trouillot, 2004; Odebeatu et al., 2006). For numerical implementation, Equation 3 (or any equivalent continuous function, depending on the SDT approach), is converted into discrete form (such as Discrete Fourier Transform) and algorithms are developed and packaged into user-friendly software. Presently, proprietary and commercial software are available such that, following initial seismic data conditioning and noise reductions, little data preparation or effort is required to get results to enhance geoscientists understanding of reservoir architecture. With present advances in technology, the practice is to test different techniques, and the method(s) for which target objectives are met is/are selected.

The frequency decomposition workflow that was adopted in this study was based on the deconvolution of Gabor wavelet with seismic trace (McArdle and Ackers, 2012) (for the deepwater studies), and CLSSA method (Puryear et al., 2012) (for the fluid contact mapping). The methods were selected after initial evaluation of various SDT methods as implemented in the software that was available for this study. We decomposed the seismic volumes into a suit of frequency cubes and then view cross-sections and horizon-based slices extracted from different frequency cubes. The optimal frequency bands upon which the target geological features were best illuminated were selected. We used the RGB (Red, Green, and Blue) display scheme as applied by Liu and Marfurt (2007) to view the high, middle and low frequency slices in a single colour image. The RGB blending workflow assigned low frequency in the Red channel, mid frequency in the Green channel, and high frequency in the Blue channel. Generally, high frequency components are sensitive to the thin layers and low frequency components are better at revealing thick layers (McArdle and Ackers, 2012). Therefore, by combining different frequency components, we could better delineate channels with different thickness (Partyka et al. 1999). Also, as part of the study, we generated RGB blended frequency volumes. This allowed shallower and deeper anomalies to be discovered, thereby generating additional opportunities for future studies.

FIELD EXAMPLES

Deepwater: Channel System Delineation

The SDT was applied to channel system delineation in two deepwater fields, offshore Niger Delta. The target reservoirs are JQ3 and BX4 reservoirs from separate geological settings.

Reservoir JQ3 consists of low impedance sands within a stratigraphically/structurally trapped mud rich turbidite system, in a mid-lower slope setting on the western flank of a shale-cored anticline structure. It consists of four weakly confined deepwater channel complexes trending NE-SW (Fig. 1). The reservoir is Upper Miocene in age and is composed of fine-grained amalgamated channel sands derived from the shelf margin. Estimated ultimate recovery for the reservoir is 130 MBO. Seismically, the reservoir is tuned as net reservoir thickness is expressed as single seismic loop events on seismic data. Figure 1a is an attribute extraction showing the reservoir deepwater channels and sample well locations. I1/P1 and I2/P2 injector/producer pairs were drilled in Channel B, whereas I3/P3 pair was drilled in Channel C. Ongoing studies seek for additional drill well opportunities in Channels A, B, C, and D. However, connectivity and sweep remain key uncertainties in development of JQ3 reservoir, making it critical to target injector/producer pairs in the same channels in the different regions.

Figure 1b shows RGB blended frequency data draped on a reference horizon representing the top of the reservoir (after Schmidt et al., 2013). We obtained 14 frequency cubes in the usable frequency band, 5 - 60 Hz, at an interval of 5 Hz. The low, middle and high frequency components are at 15 Hz, 25 Hz and 35 Hz respectively, after careful inspection of different frequency volumes. The RGB blend reveals more detail about the channel systems, highlighting associated facies and resolving internal geometries. For examples, the occurrences and geometries of late stage channel systems, especially in Channels B and C, are highly visible. New insight provided by SDT has led, in part, to interpretation that performance of the various injector/producer pairs might have been impacted by the highlighted late stage channel systems. Also, noticeable is connection between Channels B and C (Figure 1b), which were initially and otherwise thought to be entirely separated based on attribute extractions (Fig. 1a). This information is currently being integrated into well placement decisions. In addition, a good correlation has been established between well data and spatial spectral expressions on the SDT-derived RGB surface (Figure 1b). Based on well data, areas of strong and equal response from the three decomposition frequencies which appear white, correspond to sandier areas, whereas dark color, with no resulting signal at any of the chosen frequencies of the blend (McArdle and Ackers, 2012), corresponds to low net-sand areas. This information corroborates results from amplitude extraction where brighter amplitudes correspond to thick net-sands (Fig. 1a). Generally, future drill wells are being designed to target relatively thick sands, where producer/injector pairs are well connected for sustainable pressure support.

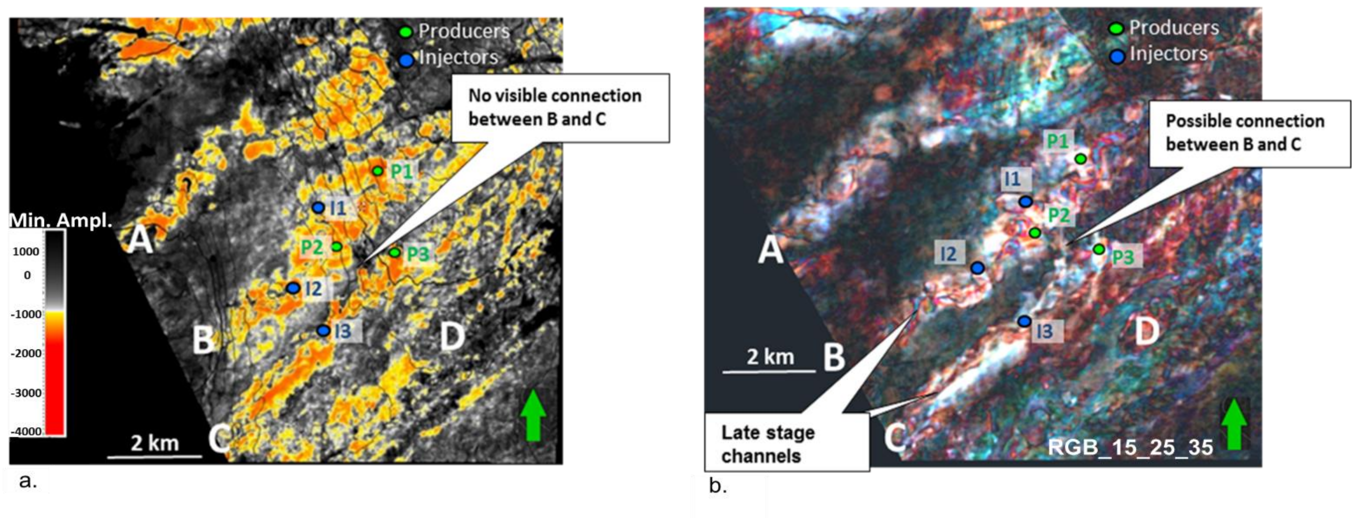

Figure 1: Reservoir JQ3 showing the producer/injector pairs; (a) amplitude extraction; (b) SDT-derived horizon-based color blend of 15 Hz, 25 Hz, and 35 Hz frequencies, as Red, Green and Blue colours, respectively.

The second case study was taken from another deepwater setting in the Niger Delta. Reservoir BX4 is an Upper Miocene sand located in a deepwater slope channel complex system. The reservoir consists of two separate fault blocks separated by a major fault. The downthrown block is penetrated by well E1X, which encountered oil in the Upper Miocene sand. Previous detailed study (Amidu et al., 2015) used well and seismic data calibrations at E1X to de-risk fluid type in the unpenetrated fault compartment in the SW fault block. Results predicted oil in upper part of the unpenetrated SW fault block close to major fault. Also, previous wedge modeling has shown that reservoir thickness is relatively below the limit of seismic resolution (Amidu et al., 2015).

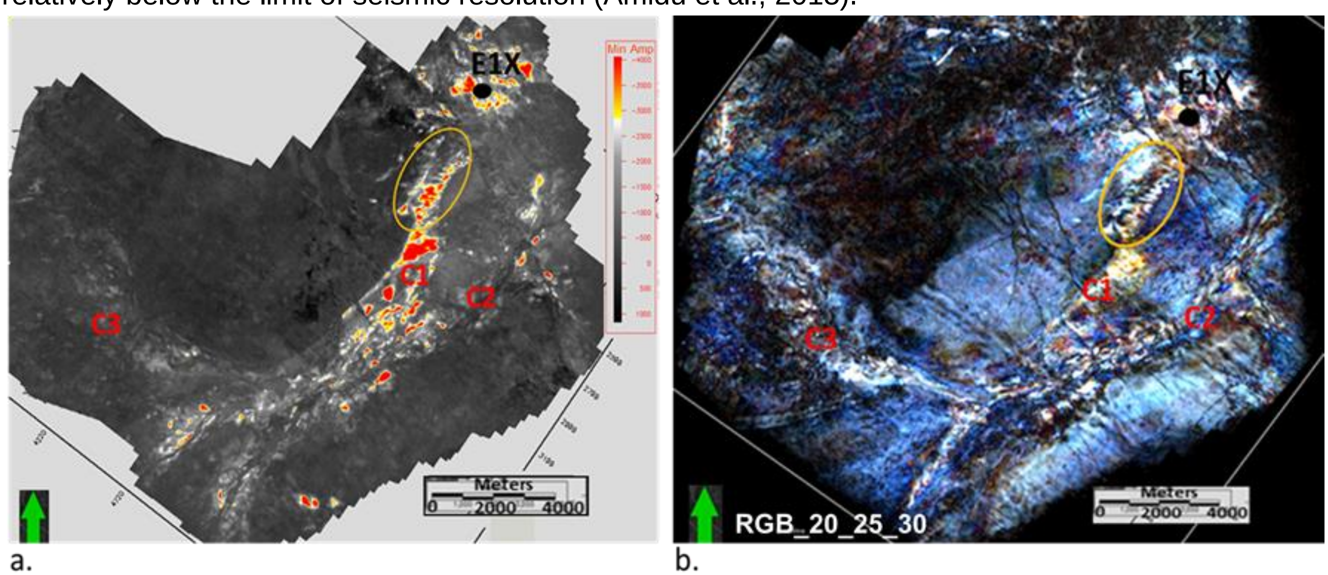

Figure 2: Reservoir BX4 showing deepwater channels and well E1X; (a) amplitude extraction; (b) SDT-derived horizon-based color blend of 20 Hz, 25 Hz, and 30 Hz frequencies.

Figure 2 shows an amplitude extraction and a horizon-based SDT-derived RGB blended frequency data from the reservoir. Improved level of details of channel patterns and locations of major faults are revealed by spectral decomposition. Two systems of channels (designated as C1 and C2) could be more clearly observed to run from NE to SW, where they merged to form bigger channel systems in the south. Also, SDT surface (Fig. 2b) shows detail geometry of branching channel C3, which was less visible in the attribute extraction (Fig. 2a). The proposed oil sand as inferred from previous study is within Channel C1 (yellow circle). The areal extent of the sand could be corroboratively inferred from both the amplitude extraction (Figure 1a) and SDT-derived surface (Fig. 1b). Overall, SDT enhanced better knowledge of internal architecture of the reservoir. The SDT information corroborates results from previous study (Amidu et al., 2015), where a drill well location was proposed in upper side of the unpenetrated SW fault block close to major fault.

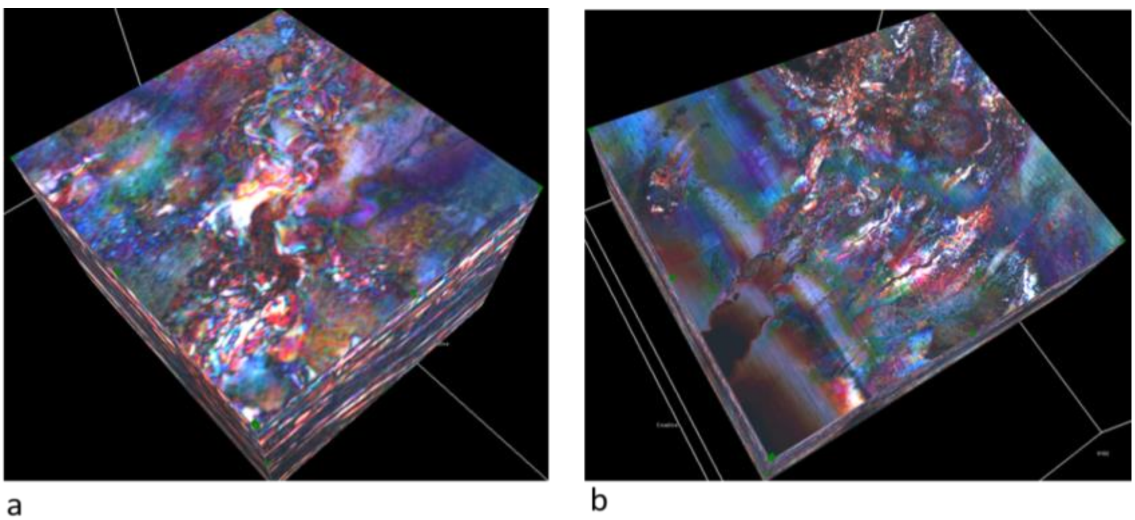

Figure 3: Examples of 3D SDT-derived RGB color blended volumes, which have been useful for field-wide quick reconnaissance to identify shallower and deeper anomalies.

Beyond the horizon-based analysis, Figure 3 shows the blended 3D frequency volumes that were generated from above highlighted studies. These volumes provided opportunity for quick reconnaissance to identify anomalies away from the zones of interest. Generally, with such 3D volumes, entire field could be studied, where shallower and deeper anomalies could be mapped at resolution higher than could be possible with conventional time-domain seismic volumes. Details of such analysis, however, are beyond the scope of the present study.

Shallow Water: Fluid Contact Mapping

We applied SDT to support presence of flat events, and to accurately map OWC and GOC on seismic volumes from BWY field in shallow water offshore Niger Delta. The field is one of the largest assets in the Niger Delta covering over 15000 acres, with over 200 wells, and a remaining reserve estimate of about 500 MBO. To effectively and accurately assess future opportunities in the field, field-wide mapping of fluid contact using seismic data was carried out.

We generated frequency volumes over a frequency range of 5 to 60 Hz at 5 Hz increment, and volumes for which the flat events were most visible were selected. Figure 4a, shows examples of cross sections through the original seismic volume and the frequency data. The interpreted GOC and OWC are visible on all the displays, though careful analysis of the various sections reveals subtle difference in information in the seismic volumes. Generally, the frequency volumes were used interactively with the stacked time-domain volume for the fluid contact mapping. By integrating all the data, both the GOC and OWC could be better mapped with confidence throughout the field.

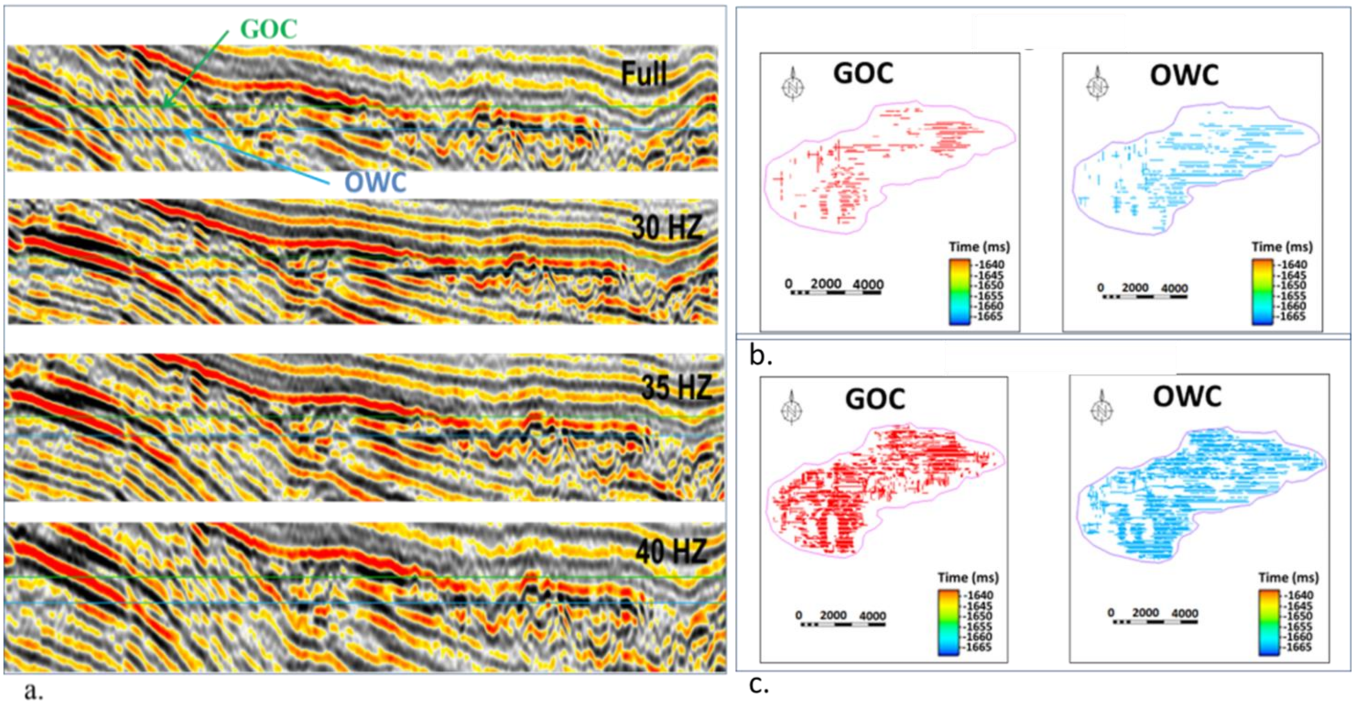

Figure 4: SDT-derived technical products for BWY field; (a) Seismic cross sections through original seismic data and frequency volumes; (b) Basemap display of mapped GOC and OWC flat events as mapped from time-domain volume; (c) Basemap display of mapped GOC and OWC flat events assisted with SDT-derived frequency volumes.

Figure 4b shows the originally mapped GOC and OWC, whereas Figure 4c shows SDT assisted maps of the fluid contacts for the field. The advantage of SDT integration into the work process is clearly visible. The SDT allowed the contact to be densely mapped, as the SDT integration allowed the flat events to be mapped with improved confidence; thereby increasing accuracy of results. The field-wide estimation of remaining oil column thickness was eventually carried out using the GOC and OWC maps. Relatively un-swept areas were characterized by higher oil column thickness, whereas low oil thickness correlated to areas with higher production impact. Results were consistent with available static and dynamic models for the field. Overall, this information has aided evaluation of remaining oil reserves, drill well planning, production optimization, and general future opportunities in BWY field.

SUMMARY AND CONCLUSION

Spectral decomposition analysis is an important imaging tool for reservoir characterization. Three field examples presented illustrate how high-resolution picture of a reservoir can be built with greater confidence to obtain better understanding of risks and uncertainties. In the deepwater examples, SDT enhanced stratigraphic details not obvious in traditional amplitude extractions. Results have improved understanding of the reservoirs architecture and thereby reducing reservoir connectivity uncertainties. For the shallow water environment case study, integration of SDT helped to improve confidence in the field-wide mapping of flat events associated with fluid contacts, and thereby enhancing accurate evaluation of future opportunities in the BWY field.

In addition, ability to generate RGB-blended 3D frequency data has helped to identify anomalies that could be the focus of future studies. With current advances in technology and availability of proprietary and commercial software, following initial data conditioning, little effort is required to get results to enhance better understanding of reservoir architecture. Nevertheless, a good knowledge of SDT fundamentals coupled with knowledge of reservoir of interest will help to guide choice of methods and ensure accuracy of SDT-derived data interpretation. Generally, improved SDT integration into shallow and deepwater studies is recommended to extract subtle information from seismic data. Presently, the technology is currently being used to support other ongoing projects in our shallow JV and Deepwater fields; adding confidence to stratigraphic and structural interpretation.

ACKNOWLEDGEMENT

The authors wish to thank Nigerian National Petroleum Corporation (NNPC) and Esso Exploration and Production Limited, Nigeria, for release of the materials and permission to publish this work. Many thanks to the Geoscience community of the Mobil Producing Nigeria Unlimited for technical reviews and suggestions.

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