Use of Spectral Decomposition in Identifying Stratigraphic Baffles that are below Seismic Resolution

[1]Abimbola Durogbitan, [1]Eyogwe Simon, [2]Onyejiuwa Ekene and [2]Ibekwe Collins
[1]Amni International Petroleum Development Company Ltd,
[2]Energy, and Mineral Resources Ltd.

ABSTRACT

During a reservoir characterization study of the ATO field, a 20-psi pressure difference was observed between two wells, X6 and X8, drilled into the F1 reservoir. Initial seismic interpretation results showed no indications of a baffle or barrier between the wells that would have caused this difference. As a result, it was essential to determine the cause of the pressure differential within the reservoir, identify any baffles or potential flow barriers and assess the possibility and degree of reservoir compartmentalization. In general, a reservoir is compartmentalized if there is a difference in fluid properties between two or more wells drilled into a single reservoir. To determine the degree of compartmentalization, dynamic production data would be the ideal approach; however, it is not readily available. As such, fluid properties such as formation pressure, fluid density, and hydrocarbon geochemistry are often used. While using these properties to determine the degree of compartmentalization works most times, the major challenge, in this scenario, is accurately defining the spatial position and extent of the compartments' boundaries, mainly when caused by lateral lithology variations or sub seismic faults. To solve this problem, we attempted to use conventional attribute analysis. However, this approach was ineffective as it was unable to highlight or delineate any flow barrier in the form of baffles of faults. As a consequence, spectral decomposition, an advanced attribute analysis method, became an appealing option because of its ability to image these subtle geologic features better. To do this, it decomposes the seismic into its constituent frequencies, making it possible to view the seismic data at different frequencies. This paper shows how we used spectral decomposition to resolve the stratigraphic baffles in the F1 reservoir, ATO field, Niger delta. This study used two spectral decomposition algorithms, Short Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT), to identify and delineate the hydraulic flow barriers. The outputs from the transforms are tuning cubes and single-frequency cubes for the peak frequencies selected from the frequency spectrum generated for the reservoir interval. Each frequency map was analyzed to identify potential faults, thickness, and later lithology variations. Based on this analysis, an RGB blend of geologically significant frequency cubes was generated, and time-slices and maps that enhanced visualization were extracted and helped identify hydraulic flow barriers within the reservoir. MDT formation pressures, together with an understanding of the reservoir's geology, were integrated to validate and interpret the results of the spectral decomposition. The frequency maps between 10Hz -26Hz show the pay zone of the F1 reservoir as a continuously connected hydrocarbon pool. The frequency map at 36Hz highlighted dark streaks within the reservoir that were extensive and trended parallel to the shoreline. We interpreted them as shale baffles, forming the flow barriers that resulted in the pressure differential between the two wells. The study shows that spectral decomposition is another cost-effective way to identify intra-reservoir and sub-seismic compartmentalization without drilling additional wells.

Keywords: Spectral decomposition, Resolution, Stratigraphy Baffles, Compartmentalization, Fourier Transform, Wavelet Transform.

INTRODUCTION

In general, a reservoir is compartmentalized if there is a difference in fluid properties between two or more wells drilled into it. It occurs when seals (structural or stratigraphic) within the reservoir impede hydrocarbon flow from one compartment to the other. Several geologic factors and fluid dynamics can create these seals, and they can be classified broadly into two – "static" or "dynamic" seals. Static seals create a permanent flow barrier between the reservoir compartments, while dynamic seals are usually low permeability flow baffles that reduce hydrocarbon flow rates significantly during production (Jolley *et al.,* 2010). As a result, reservoir compartmentalization is a significant risk that should be assessed early in the appraisal and development phases of

We thank NNPC, AMNI International Petroleum Development Company and Energy and Mineral Resources Limited for allowing the release of data, materials and for granting permission to publish the work.

a field's life cycle. If it is not discovered early enough or misunderstood, it can substantially impact field economics, development plans, and investment decisions, potentially leading to field abandonment owing to economic loss.

There are several approaches used to estimate the degree of reservoir compartmentalization. The most preferred approach is to use dynamic production data; however, this data is not readily available (Smalley et al., 1996). The typical approach uses fluid properties such as formation pressure, fluid density, viscosity, and hydrocarbon geochemistry, measured from different wells within a single reservoir (S. J. Jolley, 2010) While using this approach to estimate the degree of reservoir compartmentalization works most of the time, the main challenge is defining the spatial position and extent of the compartments' boundaries with better accuracy. It becomes considerably more difficult when the flow barriers result from subtle lateral variations in lithology and sub-seismic faults that are difficult to define using typical broadband seismic data.

During a reservoir characterization study of the ATO field, a 20-psi pressure difference was observed between two wells drilled into the F1 reservoir. Initial seismic interpretation results showed no indications of a baffle or barrier between the wells that would have caused this difference. As a result, it was necessary to understand the following; The cause of the pressure differential within the reservoir, the position and spatial extent of the flow baffles, and the implications on the field development plan.

We considered spectral decomposition an appealing option to solve these problems because of its ability to resolve subtle geologic features. It decomposes the seismic traces into their constituent frequencies, making it possible to view sections of the seismic data at different frequencies using time slices and frequency maps. A selected combination of these time slices and maps enhances the visualization of subtle features making it easier to extract detailed stratigraphic patterns that help refine the geologic interpretation of seismic data. This approach yields much higher resolution images of reservoir boundaries, lithologic heterogeneities, and interval thicknesses than the traditional full-band seismic displays (Burns and Street, 2005). Partyka et al., 1999 and Marfurt et al.,2001 successfully utilized Spectral decomposition in thin bed analysis, while Castagna et al., 2003, and Sinha et al., 2005, also used the same approach for hydrocarbon detection. Other studies also show that spectral decomposition can highlight internal reservoir heterogeneities (Laughlin et al., 2003) and understand structures and sand distribution (Ahmad et al., 2012). These studies, among others, demonstrate that spectral decomposition is a reliable technique that can be applied to solve a wide range of problems.

This paper shows how we used spectral decomposition to identify and delineate the hydraulic flow barriers within the F1 reservoir. The spectral decomposition produced single-frequency cubes as output corresponding to dominant frequencies within the interval of interest. For the reservoir of interest, an RGB blend of geologically significant frequencies was created, and time slices and frequency maps were also generated. Well logs, MDT formation pressures, and an understanding of the local geology of the area were integrated to validate the results of the spectral decomposition.

The findings of this study demonstrate the effectiveness of spectral decomposition in locating subtle stratigraphic baffles within the F1 reservoir. These shale baffles were the likely source of the observed pressure discrepancy between wells X6 and X8.

REGIONAL GEOLOGY

The study area lies within the offshore of the Tertiary Niger Delta. The Niger Delta basin (Figure 1) is situated in the Gulf of Guinea and extends throughout the Niger Delta Province of Nigeria, as defined by Klett (1997). The clastic wedge of the Niger Delta occurs along a failed arm of a triple junction system that formed initially during the period of a breakup between the plates of South America and Africa. This process occurred in the Late Jurassic (Doust and Omatsola, 1990). Synrift sediments accumulated from the Cretaceous to the Tertiary periods, with the oldest dated sediments from the Albian period. The delta has since prograded southwestward from the Eocene to the present, generating depobelts representing the most active delta region at each stage of its development (Doust and Omatsola, 1990). The Niger delta

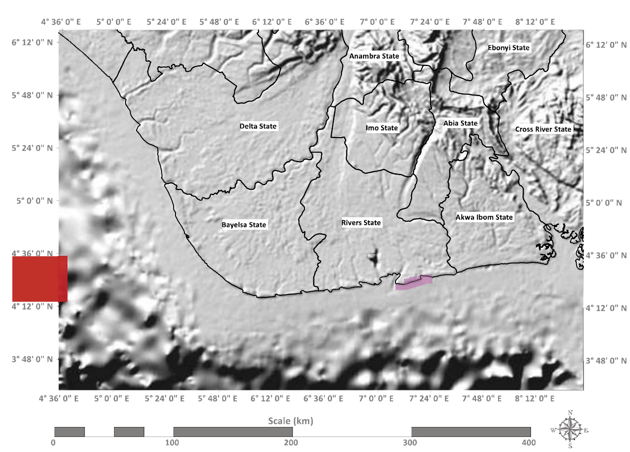

Figure 1: Map of the Niger delta basin, the location of the study area.

comprises three primary formations, Benin, Agbada, and Akata. The three formations represent sedimentary deposition in three different environments: continental, transitional, and marine (Short, *et al.,* 1967). The movement of deep-seated, over-pressured, ductile Akata marine shale throughout the basin generated normal faults. As a result, the province's structures are primarily syn depositional. Growth faults, rollover anticlines, and shale diapers are examples. Ekweozor (1994) states that the Tertiary Niger Delta (Akata - Agbada) Petroleum System is the only petroleum system known to exist in the Niger Delta Province.

RESERVOIR GEOLOGY

Generally, the depositional environment of the F1 reservoir was defined using core reports, well logs motifs, and petrophysical properties. The F1 reservoir was deposited in a shelf /storm, wave-dominated shoreface environment based on descriptions and summaries from core reports. Sediments deposited in this environment are often thick and relatively homogeneous, with a high degree of lateral continuity in a shore-parallel orientation. However, perpendicular to the shoreline, the lateral continuity can be broken by shale baffles depending on the interaction between sediment supply and relative sea level. Initial seismic interpretation.

The F1 reservoir corresponds to a trough on seismic, as seen in Figure 2. This reflector was interpreted over the Ato field boundary, and we show the resulting reservoir time structure map in Figure 2. The RMS attribute extraction along the reservoir's top shows bright, fairly consistent amplitudes that conform to the structure showing the hydrocarbon-bearing interval of the reservoir. The MDT Pressure data taken from two wells within the reservoir, X6 and X8, showed a 20psi pressure differential, implying that the wells exist in separate pressure compartments (Figure 4). A detailed analysis of the RMS amplitude around the X6 and X8 wells showed no evidence of shale baffles or faults within the reservoir (Figure 5). Our inability to identify potential flow barriers within the reservoir remained a significant uncertainty as the reason behind the pressure difference could not be defined.

Theory

<u>Fourier Series and Fourier Transform</u>

Any periodic function f(t) can be expressed as an infinite sum of sine and cosine functions with increasing frequency using the Fourier series. The Fourier series is expressed mathematically as:

$$f(t) = \frac{A_0}{2} + \sum_{k=1}^{\infty} A_k\, cos(2\pi kt) + B_k\, sin(2\pi kt)$$

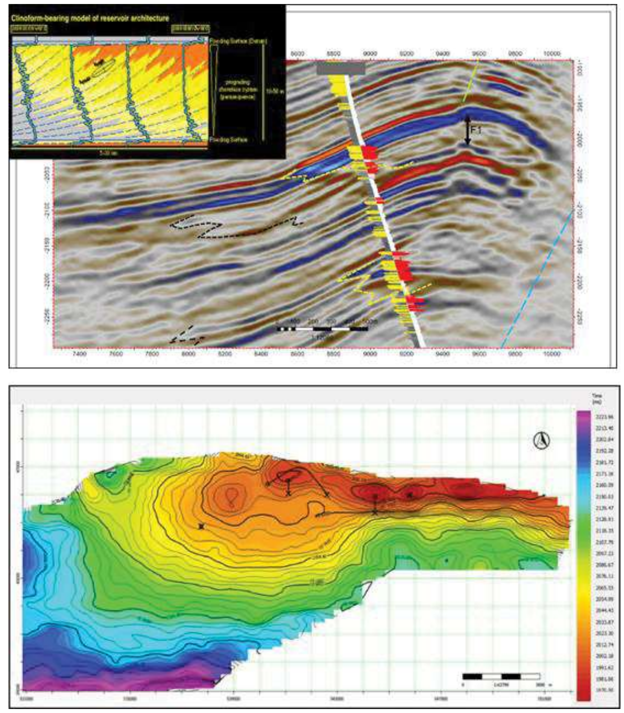

Figure 2: a) A Seismic section and well log showing the F1 reservoir. b) F1 reservoir time structure map.

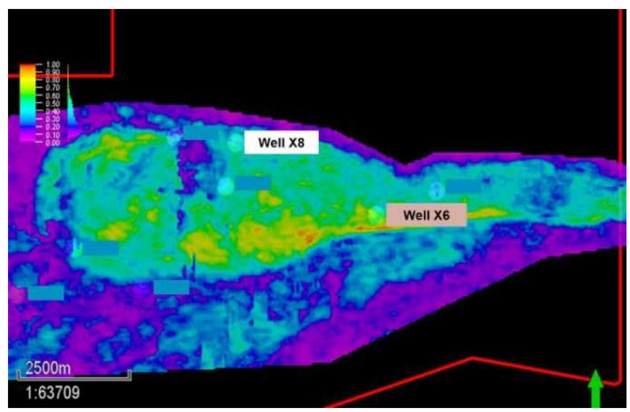

Figure 3: RMS amplitude extraction along the top of the F1 reservoir.

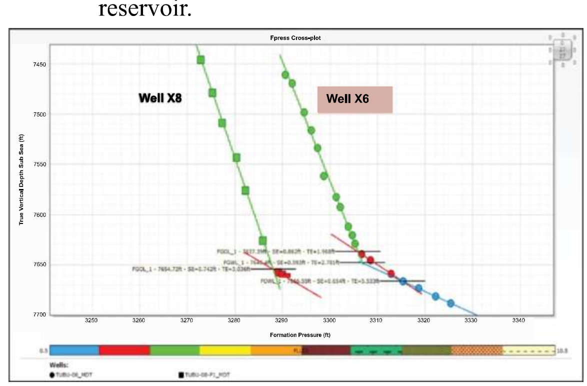

Figure 4: MDT Pressure from Well X06 and Well X08 showing 20 psi pressure differential within the F1 reservoir.

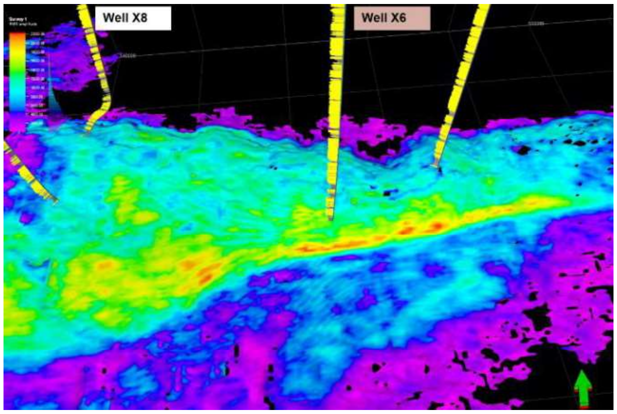

Figure 5: Zoomed in 3D high-resolution RMS attribute map.

The Fourier transform converts the same function from the time domain to the frequency domain. The Fourier transform of the function f(t) is expressed mathematically as:

$$f(\omega) = \left[f(t), e^{i\omega t}\right] = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt$$

Converting a signal to the frequency domain with the Fourier transform provides an overall frequency behaviour of the signal, assuming it is stationary; however, the limitation of this transform is that it is insufficient for studying non-stationary signals, whose frequency varies with time, such as seismic data.

Short Time Fourier Transform (STFT)

The short-time Fourier transform (STFT), a modification of the Fourier transform, overcomes this limitation by dividing the signal into short windows and performing the Fourier transform on each window. It simply decomposes a signal by using a series of short, overlapping time windows with a fixed length, and performs the Fourier transform on each of the time windows providing the frequency content of the signal at that period. The STFT is simply the inner product of the signal f (t) with a time-shifted window function and is expressed mathematically as:

$$STFT(\tau, \omega) = \int_{-\infty}^{\infty} f(t)\emptyset(t-\tau)e^{-i\omega t}dt$$

Continuous Wavelet Transform (CWT)

The Continuous Wavelet Transform (CWT), introduced by Morlet et al. (1982), decomposes seismic data using a variable window length, as opposed to the short-time Fourier transform (STFT), which employs a fixed window. This method improves the time-frequency resolution. The wavelet transform method compares the input seismic signal to a mother wavelet by taking the inner product of the two and is expressed mathematically as:

$$W(a, \tau) = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{\sigma}}\Psi\left(\frac{t-\tau}{\sigma}\right)dt$$

MATERIALS AND METHODOLOGY

The data used in this study is a post-stack time migrated (PSTM), zero phase, American polarity, 3D seismic dataset with a frequency range of 0-100 Hz. It covers an area of approximately 449.98 km2 and a vertical extent of 0-5800ms. Other data used for this study include well logs, pressure data, reservoir tops, and mapped time horizons for all reservoirs. An interval of interest between 2100ms and 2700 ms was selected based on the reservoir levels and imported horizons. We extracted the instantaneous frequency attribute within this interval to provide preliminary insight into the frequency distribution within the seismic data. An amplitude spectrum showing the frequency distribution within the interval of interest was created using the Fast Fourier Transform (FFT) algorithm (Figure 6). Dominant frequencies were selected using this amplitude spectrum, and single-frequency cubes were generated for each frequency using the STFT and CWT spectral decomposition algorithms. The short-time Fourier transform (STFT) was done using these parameters; a window length of 150ms, a step size of 5ms, and a Hann taper with a 50ms length. The continuous wavelet transform (CWT) was done using a complex morlet wavelet with a bandwidth of 30. We compared the frequency cubes generated using both methods and selected the method with the better time-frequency resolution.

To create single frequency maps for the F1 reservoir, we did a horizon extraction from each frequency cube and gridded it to generate the frequency maps. These maps were examined for subtle geologic features that indicate the presence of subtle faults, baffles, or lateral lithology variations. The output frequency maps were compared to the RMS attribute map and its initial interpretation for the same reservoir. They were then calibrated to well information, which provided ground truth information to constrain our interpretation. Finally, the discrete frequency maps were analyzed, and the three geologically significant frequency maps that best illuminated the target geologic features were selected. An RGB blend colour scheme was used to view the high, middle, and low-frequency maps and slices in a single colour image. The low-frequency component was assigned to the red channel, the middle-frequency component to the green channel, and the high-frequency component to the blue channel. The RGB blended map and time slices were then processed and interpreted first to find any potential sub-seismic faults. Then delineate any lateral lithology changes or internal heterogeneities that could have caused the pressure difference in the F1 reservoir based on the Laughlin et al. 2003 paper. Additional inferences were also made, such as thickness variations within the reservoir.

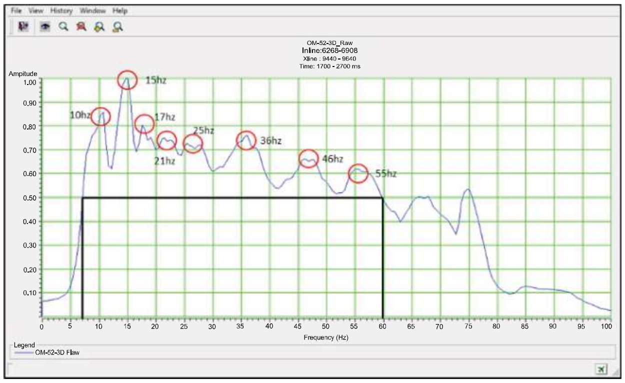

Figure 6: Amplitude spectrum of the cropped volume showing dominant/peak frequencies within the interval of interest.

RESULTS AND DISCUSSION

Figure 6 shows the extracted amplitude spectrum from the interval of interest. The figure shows that the seismic data has a frequency bandwidth of 7Hz to 60Hz, defined by taking the frequency range at half the amplitude spectrum. Eight isolated peaks were observed on the amplitude spectrum corresponding to the dominant frequencies within the interval of interest. Figure 7a and Figure 7b compares a 10Hz frequency section generated using the two different spectral decomposition methods. In addition, we compared the other frequency cubes from both methods to help determine the method with a better time-frequency resolution. The STFT method has a high-frequency resolution but a low vertical resolution, making it difficult to pinpoint the actual position of an event in time on the seismic data **(**Figure 7a and Figure 7b**).** On the other hand, the CWT method improved time resolution while maintaining frequency resolution **(**Figure 7a and Figure 7b**).** Comparing both methods showed that the CWT method provided a better time-frequency resolution; this method's results were used to complete the entire analysis.

Figure 8 shows the eight discrete single-frequency maps created for the F1 reservoir. The maps at different frequencies highlight different parts of the reservoir, showing subtle variations in reservoir thickness and possible internal heterogeneities within the reservoir. In this case, the lower frequencies highlight the thickest areas of the F1 reservoir, whereas higher frequencies highlight the reservoir's relatively thinner parts.

The 10Hz frequency map is shown in Figure 9 . Using well log data as calibration, the red colour on the map correlates to hydrocarbon-bearing sands, whereas the cool colours, yellow to blue, reflect wet sands within the reservoir. We also observed how it compares and shows similar results with the RMS attribute shown in Figure 3 , which show no

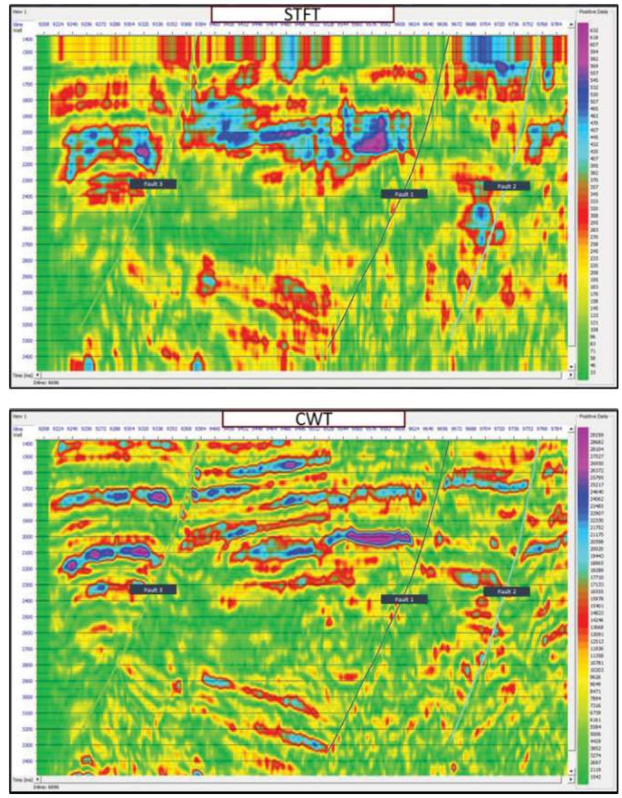

Figure 7: A) Seismic section showing the Short-Time Fourier Transform (STFT) @ 10 Hz. B) Seismic section showing the Continuous Wavelet Transform (CWT) @ 10 Hz

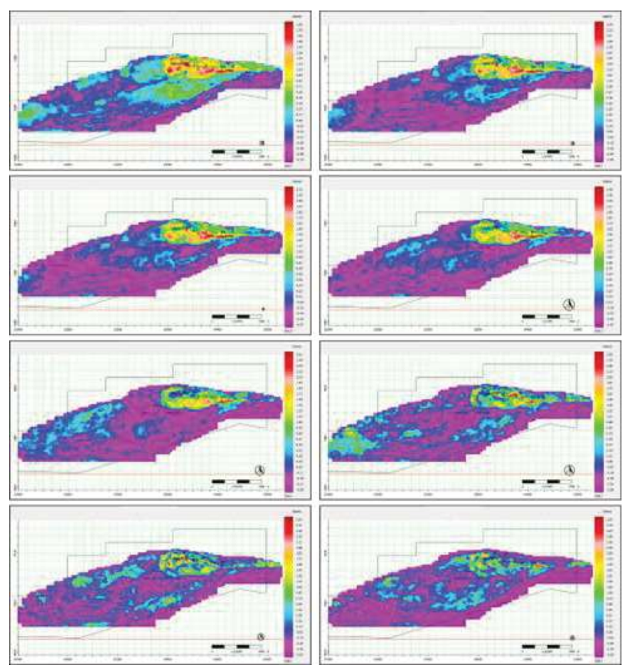

Figure 8: single frequency maps for the F1 reservoir.

indication of any flow barriers. The F1 reservoir frequency map at 25Hz, responded better to hydrocarbon fluid presence when compared to the amplitude map at 10Hz. It shows a clear contrast between the gas-oil contact and the oil-water contact (Figure 10). The hottest colour on the map corresponds to gas, while the greenish/yellowish colour represents oil. The fluid types were confirmed well logs. The frequency map at 36Hz showed dark streaks within the bright amplitude represented by the black dotted lines (Figure 11). These dark streaks occur clearly between the X6 and X8 wells, have an east-west trend (shore parallel), and are seen to be laterally extensive throughout the F1 reservoir. We interpreted these dark streaks to be minor shale baffles within the reservoir. Analysis of satellite images west of the study area reveals similar present-day features in shoreface environments. The shore parallel shale baffles are interpreted to compartmentalize the sands around the strand plains in a shoreface environment. Therefore, the F1 reservoir comprises high-quality sandstones deposited in the upper shoreface and separated by shore-parallel shale barriers formed during minor sea level incursions.

After examining the amplitude maps at all ten generated frequencies, the three geologically relevant frequencies were determined to be 10Hz, 25Hz, and 36Hz. Therefore, an RGB blend of the three geologically relevant frequencies (10Hz, 26Hz, and 36Hz) was created. The red channel was assigned a frequency of 10Hz, the green channel at 26Hz, and the blue channel at 46Hz. The RGB map for B-01 displays the intensity of each colour, which represents the contribution of each spectral frequency band. Warm colours, ranging from red to yellow, imply a more substantial contribution from lower frequencies, 10Hz and 26Hz. We attributed these colours to the thickest sections within the F1 reservoir, which contain high-quality sands and hydrocarbons. The Cool colours, ranging from green to purple, indicate contributions from higher frequency (36Hz).

The RGB time slice at 2020 ms through the F1 reservoir showed lateral variations in frequency response within the hydrocarbon-bearing interval indicated by colour variations. We attributed these lateral variations to most likely be due to variations in lithology properties within the reservoir.

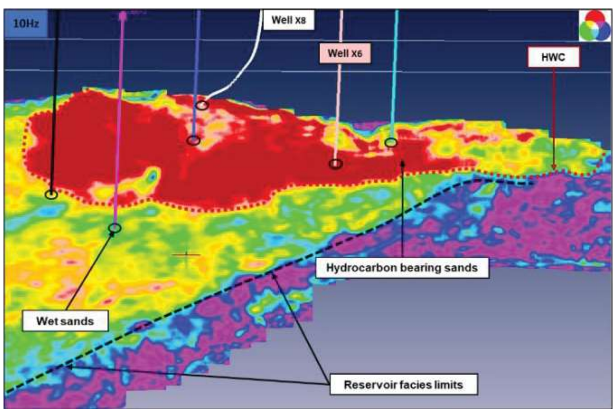

Figure 9: The F1 reservoir frequency map at 10Hz.

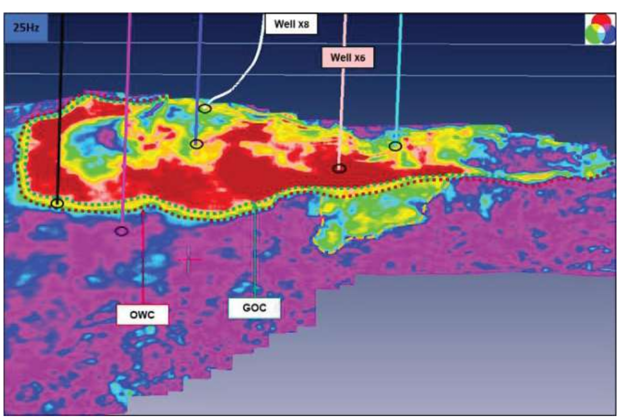

Figure 10: The F1 reservoir frequency map at 25Hz.

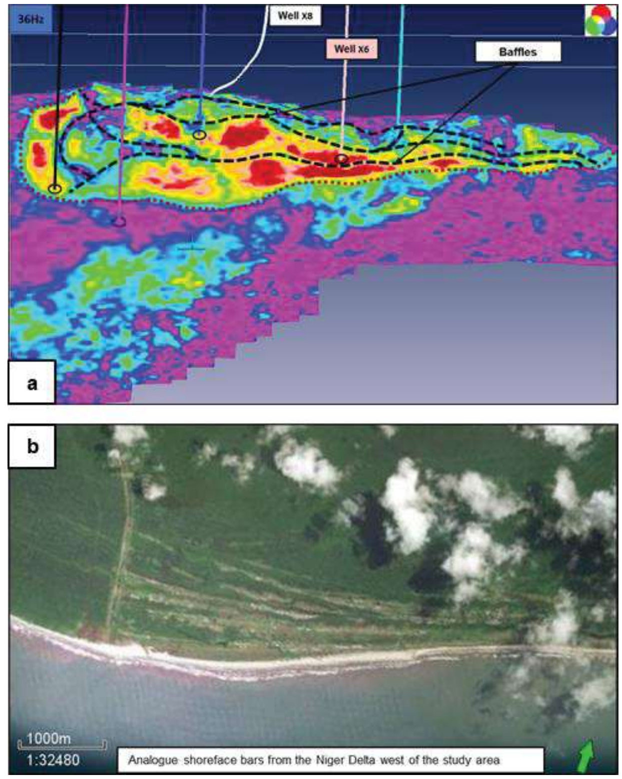

Figure 11: The F1 reservoir frequency map at 36Hz.

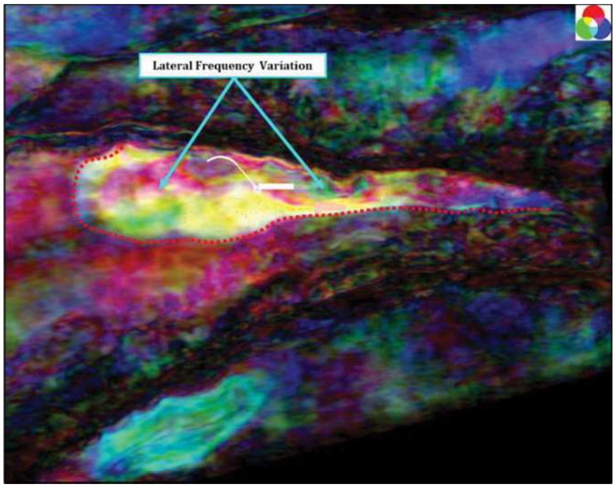

Figure 12: RGB Blend of Spectral Decomposition 10 Hz (Red), 26Hz (Green) and 46 Hz (Blue) for F1 reservoir.

CONCLUSION

The spectral decomposition technique was applied to the F1 reservoir and successfully resolved the problems mentioned earlier:

- The cause of the pressure differential within the reservoir.
- The type, position, and spatial extent of the flow baffle caused the observed pressure differential.
- The implications on the development plan for this reservoir.

This study demonstrates that incorporating spectral decomposition into reservoir compartmentalization analysis is a cost-effective method of identifying intra-reservoir lithology variation and sub-seismic faulting that led to compartmentalization without drilling extra wells. This approach improves the overall approach for delineating flow barriers within reservoirs that are not clear on conventional seismic data. It aids the process of identifying these subtle features and defining their position, spatial extent, and trend. Finally, we recommend that spectral decomposition be used in conjunction with other conventional methods for determining the degree of compartmentalization to get the best results and accurately define reservoir compartments.

REFERENCES CITED

Burns S. and Street, K Spectral decomposition highlights faults [Journal]. - 2005.

Diego Hernandez John Castagna Stratigraphic detection and hydrocarbon detection in offshore Gulf of Mexico Miocene [Conference] // SEG Int'l Exposition and 74th Annual Meeting. - Denver, Colorado : [s.n.], 2004.

E.M Ekweozor C.M. and Daukoru Petroleum source-bed evaluation of Tertiary Niger Delta. [Journal]. - [s.l.] : AAPG, 1984. - Vol. 68.

Greg Partyka James Gridley and John Lopez Interpretational applications of spectral decomposition in reservoir charaterization [Journal] // The Leading Edge. - 1999.

Kenny Laughlin Paul Garossino, and Greg Partyka 'Spectral Decomposition for Seismic Stratigraphic Patterns*' in Spectral Decomp Applied to 3-D. [Journal] // AAPG Explorer . - 2002.

Kirlin K. J. Marfurt and R. L. Narrow-band spectral analysis and thin-bed tuning [Journal]. - 2001.

Mohammed Farfour Wang Jung Yoon and Youngeun Jo Spectral decompostion in Illuminating Thin Sand Channel Reservoir, Alberta,Canada. [Journal] // Canadian Journal of pure & applied sciences.. - 2012.

Morlet J., Arens, G., Fourgeau, E. and Giard, D. Wave propagation and sampling theory—Part I: Complex signal and scattering in multilayered media [Journal] // Geophysics, 47. - 1982. - pp. 222-236.

Rowell Mirza Naseer Ahmad and Philip Application of Spectral Decomposition and Seismic Attributes to Understand the Structure and Distribution of Sand Reservoirs within Tertiary Rift Basins of Gulf of Thailand [Conference] // AAPG Annual Convention and Exhibition. - Long Beach, California : [s.n.], 2012.

Rowell1 Mirza Naseer Ahmad1 and Philip Application of Spectral Decomposition and Seismic Attributes to Understand the Structure and Distribution of Sand Reservoirs within Tertiary Rift Basins of Gulf of Thailand [Conference] // AAPG Annual Convention and Exhibition. - Long Beach, California : [s.n.], 2012.

S.J. Jolley Q.J. Fisher, R.B. Ainsworth Reservoir compartmentalization: an introduction [Journal] // Geological Society London Special Publications. - 2010.

Satish Sinha Partha S. Routh, Phil D. Anno, and John P. Castagna Spectral decomposition of seismic data with continuous-wavelet transform [Journal]. - 2005.

Short K C and Stauble A J Outline Geology of the Niger Delta [Journal] // AAPG Bulletin. - 1967. - pp. 761-779.

Stauble K. C. Short and A. J. Outline of Geology of Niger Delta [Journal]. - [s.l.] : AAPG, 1967. - Vol. 51.

Whiteman Arthur Nigeria: Its Petroleum Geology, Resources and Potential [Book]. - London : Graham & Trotman Ltd, 1982.