Detecting Reservoir Compartmentalization from Cepstral Decomposition

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Abstract: This study presents a novel workflow aimed at delineating subtle faults and indicators of their sealing capacity and detecting reservoir compartmentalization directly from seismic data in "Olumi" field, Niger Delta. Conventional structural interpretation of seismic and well log data over "Olumi" field was done using OpendTect and IHS Kingdom Advanced software. Cepstral Decomposition was introduced and applied to a fault model and 3-D seismic data using a developed algorithm within Mathlab software. The outputs of the conventional and developed techniques were tested on both standard and general interpretation platforms. The results showed three (3) reservoir sands (OLA 500, OLA 1000 and OLA 1500), identified across wells with average thicknesses of 4.88, 18.75 and 38.25 m respectively. Nine faults marked A, B, C, D, E, F, G, H and I were mapped in the study area including two structure building faults (A and D) which characterize the field. Four horizons (AS, BS, CS and DS) were mapped on vertical seismic sections at 2.25 s, 2.44 s, 2.76 s and 2.85 s respectively based on log interpretation. Analysis of the cepstral attributes of Gamnitude, Quefrency and Saphe of the mapped reservoirs, indicated possible compartments within reservoir sand OLA 1000 bounded by micro faults which may be responsible for fluid migration up dip into the overlying formation, thus, indicative of a ruptured seal. This study concluded that field appraisal and delineation of reservoir compartmentalization in stratigraphically and geologically complex reservoir targets could be achieved using Cepstral Decomposition attributes.

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1. Introduction

Faults play an important role in reservoir compartmentalization and can have a significant impact on recoverable volumes. On three dimensional seismic data, fractures and faults manifest as sudden, gradual, and subtle changes of seismic amplitudes. Authors such as Walden (1994) (Spectral clustering for edge detection) and Partyka *et al.* (1999) (Spectral Decomposition) have presented techniques for identifying sudden and gradual changes.

Hydrocarbon prospects that are faulted have numerous special risks. Faults can be structural (mega) or stratigraphic (micro) in size. Considerable efforts are commonly made by seismic interpreters to identify and map faults. This is however a first step toward evaluating and characterizing hydrocarbon entrapment.

Technical interpretations often stop after identifying the fault plane in the mistaken belief that the fault plane itself creates a lateral seal. The fault itself is only a representation of the narrow discontinuity where capillary properties, fluid properties and structural dips of the co-joined rock layers have a high probability of being altered. (Downey, 1990).

Fault closure-dependent prospects are capable of providing extremely large and excellent accumulations, but are inherently more "risky" than anticlinal traps. The "risk" is created by the imperfect understanding of which fault closures make excellent traps and which allow leakages (Downey, 1990).

In order to guide prospect evaluation and characterization, it is necessary to consider when a fault plane behaves as an open fracture or otherwise. There are evidences that over time, fields evolve mechanically as they deplete resulting in changes in stress configuration, fault behavior, compaction and hence compartmentalization; which are commonly not predicted at inception (Fox and Bowman, 2010).

The segregation of a petroleum accumulation into a number of individual fluid/pressure compartments occurs when flow is prevented across 'sealed' boundaries in the reservoir caused by 'static' or 'dynamic seals'. The latter allow fluids and pressures to equilibrate across a boundary over geological time-scales, but act as seals over production time-scales, because they prevent cross-flow at normal production rates such that fluid contacts, saturations and pressures progressively segregate into 'dynamic' compartments.

The effect of reservoir compartmentalization on fluid flow throughout field life has not been effectively identified or predicted. As hydrocarbon reserves become harder-to-find coupled with the attendant increasing development costs, it is important to have a strategy in place to delineate compartmentalization and mitigate uncertainties and risks associated with them.

This study presents the outcome of a new and practical method for seismic data interpretation using efficient combinations of seismic attributes and a time-frequency domain transform such as Cepstral Decomposition. This is a high resolution and optimal technique for mapping faults of varying sizes and at different scales often masked or bypassed after conventional seismic data interpretation with a view to establishing their sealing efficiency detecting reservoir compartmentalization thereby characterizing hydrocarbon reservoir, minimizing drilling risks and cost, especially now that exploration activities are shifting to deep offshore which have attendant complex geology.

2. Geology of the Study Area

"Olumi" field is located offshore Western Niger Delta Basin, Nigeria (Figure 1). The Niger Delta lies mainly in the Gulf of Guinea to the South-West of the Benue Trough. It is located between latitude 4^0 N and 6^0 N and longitude 3^0 E and 9^0 E in Southern Nigeria (Nwachukwu and Chukwura; 1986).

The Niger Delta covers an area exceeding 105,000 km^2 (Avbovbo, 1978) and it extends in an East-West direction from South-Western Cameroun to the Okitipupa Ridge. Its apex is situated southeast of the confluent of the Niger and Benue Rivers (Adagunodo et al., 2017).

The Akata, Agbada and Benin Formations make up its lithostratigraphic sequence (Avbobvo, 1978; Doust and Omatola, 1990). Rollover anticlines and structure building growth faults are common structural styles in the Niger Delta (Figure 2). The interplay between rates of sediment supply and subsidence has controlled stratigraphy and structure all through the Niger Delta's geologic history. Eustatic sea-level changes and climatic variations in the hinterland have greatly influenced the rates of sedimentation (Figure 2). Initial basement morphology and differential sediment loading of unstable shale have largely controlled subsidence in the area (Doust and Omatsola 1990).

Theory of Cepstral Decomposition

According to (Sheriff, 2002), cepstrum is the Fourier transform of a Logarithmic Frequency distribution.

Let ↔ indicate a Fourier transform operation. If $\hat{g}(t) \leftrightarrow G(\omega)$, the Cepstrum $g(\zeta)$ is

$$\hat{g}(\zeta) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left[\ln[G(\omega)] + j\gamma(\omega)\right]\ell^{j\omega\zeta}d\omega \qquad (1)$$

The transform is usually carried out in three (3) steps

$$\hat{G}(\omega) = \ln[G(\omega)] = \ln|G(\omega)| + j\gamma(\omega)G(\omega) \qquad (2)$$

$$\hat{G}(\omega) \leftrightarrow \hat{g}(\zeta) = \left(\frac{1}{2\pi}\right)\int_{-\infty}^{\infty}\left[\ln[G(\omega)] + j\zeta(\omega)\right]\ell^{j\omega\zeta}d\omega \qquad (3)$$

The inverse transform is

$$\hat{g}(\zeta) \leftrightarrow \hat{G}(\omega) = \int_{-\infty}^{\infty} g(\zeta)\, e^{-j\omega\zeta}\, d\omega\zeta, \qquad (4)$$

$$G(\omega) = \exp[\hat{G}(\omega)], \qquad (5)$$

$$g(t) \leftrightarrow G(\omega). \qquad (6)$$

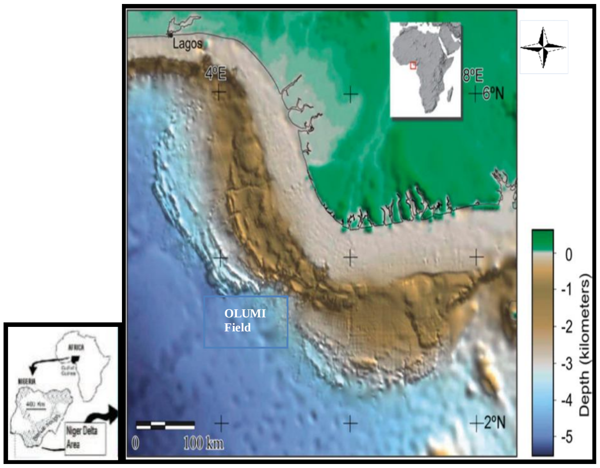


Figure 1. Niger Delta sea-floor image showing the location of the study area. (Modified from Corredor *et al*., 2005).

The variable $\hat{\gamma}$ is called Saphe and ζ is called the Quefrency (being permutations of phase and frequency; as cepstrum is of spectrum) (Sheriff, 2002). The Cepstral domain is often indicated by the hat. The transform can also be expressed as Z-transforms (Sheriff, 2002). Hall and Trouillot, (2004) applied Cepstral Decomposition to synthetic data whereas in this work, the Cepstral Decomposition has been successfully applied to field data (3-D seismic data). Cepstral Decomposition was applied to a computed fault model and 3D seismic data from the study area, and their diagnostic ability and limitations noted. The transform algorithms was integrated into an optimal algorithm whose resolving capacity was determined by computing the Spectral and Cepstral attributes of a thin bed reservoir representing lateral variations in lithofacies or similar geologic situations.

The analysis window must be long enough to give reasonable frequency resolution, but short enough to isolate the stratigraphic interval of interest. As always, indiscriminate and offhand application could result in errors; pitfalls include having insufficient bandwidth, or a window of inappropriate length (Hall and Trouillot, 2004).

3. Materials and Method

The materials for the study; a three dimensional (3-D) seismic volume, a suite of well logs and check shot data for six wells (TMB 001, TMB 002, TMB 003, TMB 004, TMB 005 and TMB 006) were obtained from Department of Petroleum Resources (DPR).

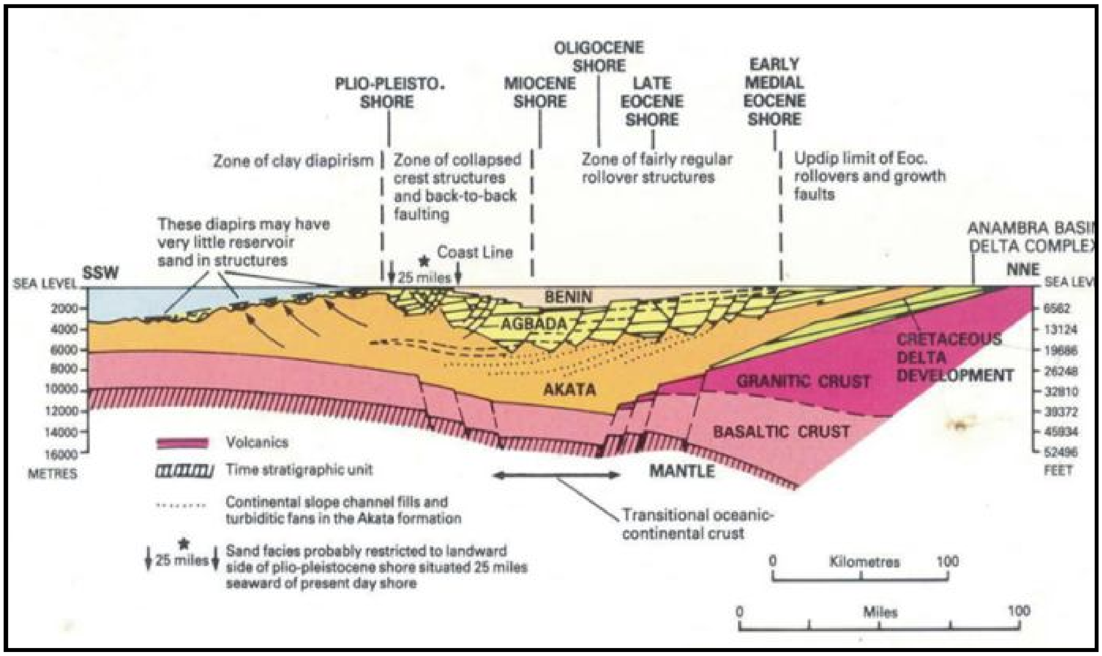


Figure 2: Generalized dip section of the Niger Delta detailing subsurface Formations and structural styles (Adapted from Whiteman, 1982)

The in-lines (dip lines) ranged from 5800 to 6200 and the cross-lines (strike lines) ranged from 1480 to 1700 covering a total area of 71.33 km^2 with line spacing of 2.5 km (Figure 3). The 3-D seismic data volume was supplied in SEG-Y format, while the well log data were given in LAS format. The Seismic data and Well log data were loaded into the IHS Kingdom Advanced and OpendTect software. In other to detect subtle faults and other changes in the seismic data over the study area, the following techniques were adopted:

i. Conventional structural interpretation (time) for strata reconnaissance and comprehension was done using the IHS Kingdom Advanced and OpendTect Software. Horizontal sections (time slices) were generated at time levels close enough to the horizons of interest to establish the framework upon which fault interpretation will occur. Faults were interpreted on the basis of abrupt termination of events on vertical seismic sections. Horizon mapping was then carried out at identify reservoir tops from well logs on the 3-D seismic data volume after well to seismic tie. After picking of faults and mapping of horizons, structure (time and depth) maps were then generated at the horizons.

ii. In the Cepstral domains, Fast Fourier Transform (FFT/DFT) was used for computational efficiency.

Cepstral attributes were computed by taking the spectrum of the logarithm of the discrete Fourier transform (DFT) of the input data following the treatment by Hall, (2006). This was done by applying the Cepstral Decomposition via a developed computer algorithm on Mathlab software. The resolving capacity of the Cepstral algorithm was determined by computing attributes of a modeled normal fault. The fault was evaluated using a 40 Hz Ricker wavelet convolved with a three layer reflectivity series. The faulted layer bearing the gas filled sandstone lens is silty shale and it is embedded in marine shale (Figure 4).

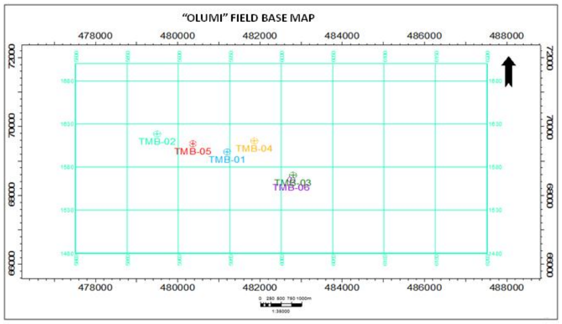


Figure 3: Base map of "Olumi" field showing the positions of the wells

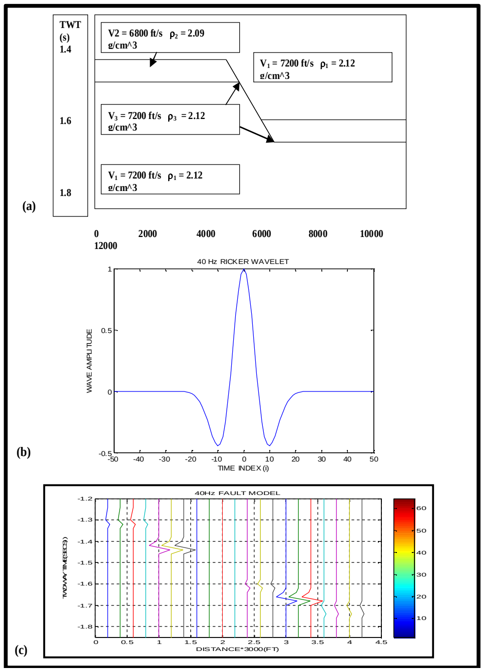


Figure 4: Fault model: (a) Geometry (b) 40 Hz Ricker Wavelet (c) Conventional section

4. Results and Discussions

Three sands marked OLA 500, OLA 1000 and OLA 1500 (Figure 5) were identified on the basis of log signatures of the gamma ray and resistivity logs. Horizontal seismic sections (time slices), were generated at 1500, 1700, 2100 and 3000 ms (Figures 6a, b, c and d). These horizontal sections showed the spatial distribution of seismic amplitude over the field depicting smeared lineaments which may be indicative of ruptured seal. Amplitude intensity is shown by the colors; highest amplitude being orange color and the lowest amplitude, dark colored areas. The high amplitude patterns observed as orange color streaks/lineaments are the faults mapped in "Olumi" field. These orange color streaks along the fault line are possible indication of leakage of hydrocarbon. As horizontal slices proceed to 1700 ms (figure 6b), the fault framework became more visible. The time slices at 2100 ms (Figure 6c) showed better resolution of the distribution of the faults across the field. Detailed fault mapping, carried out over the study area revealed that the area is highly faulted which is typical of the tectonic setting of the Niger Delta. Nine faults marked A, B, C, D, E, F, G, H and I were mapped in the field. Two structure building faults (A and D) characterize the field. Fault C is an antithetic fault trending northwest to southeast.

Four (4) reflection events (AS, BS, CS and DS) were picked on the seismic sections based on log interpretations. The horizons AS, BS, CS and DS were mapped at 2.250 s, 2.440 s, 2.760 s and 2.850 s respectively.

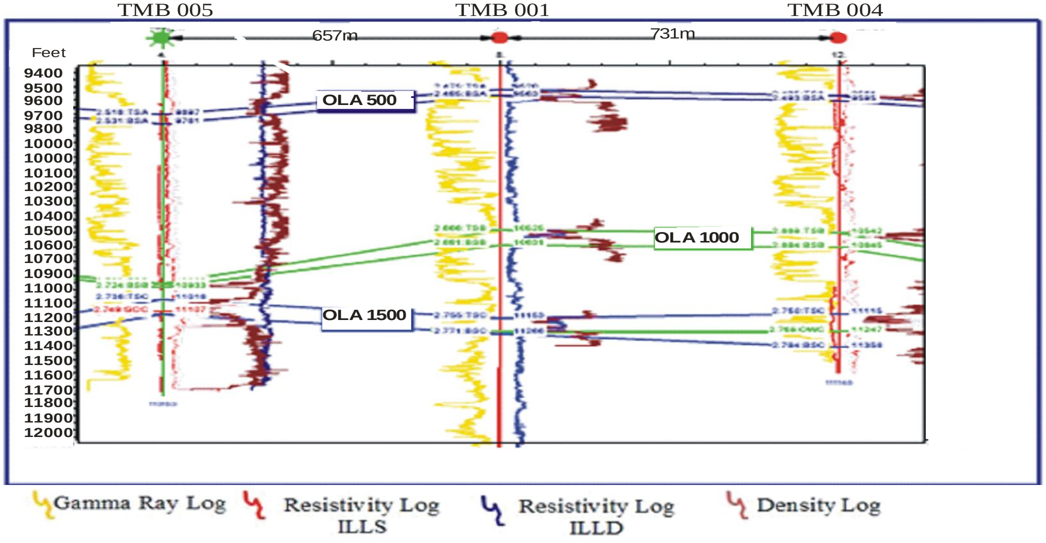


Figure 5: Lithology and Hydrocarbon Bearing Sand Correlation in "Olumi" Field (IHS Kingdom Advanced)

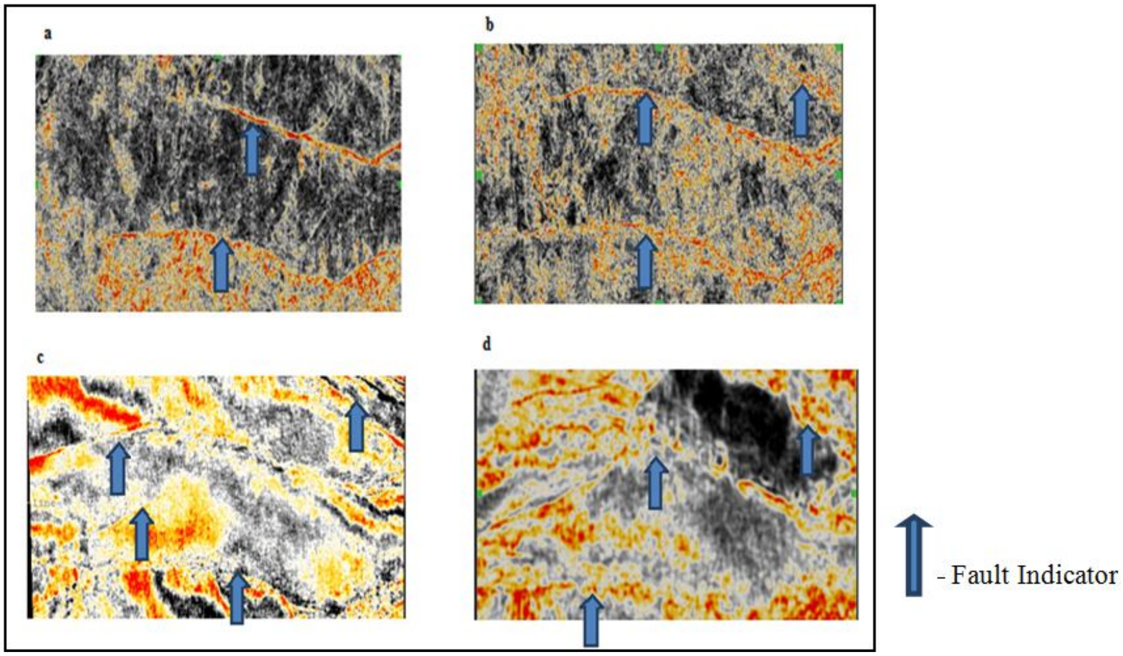


Figure 6a-d: Horizontal sections (time slices) at 1500 ms, 1700 ms, 2100 ms, and 3000 ms respectively (OpendTect).

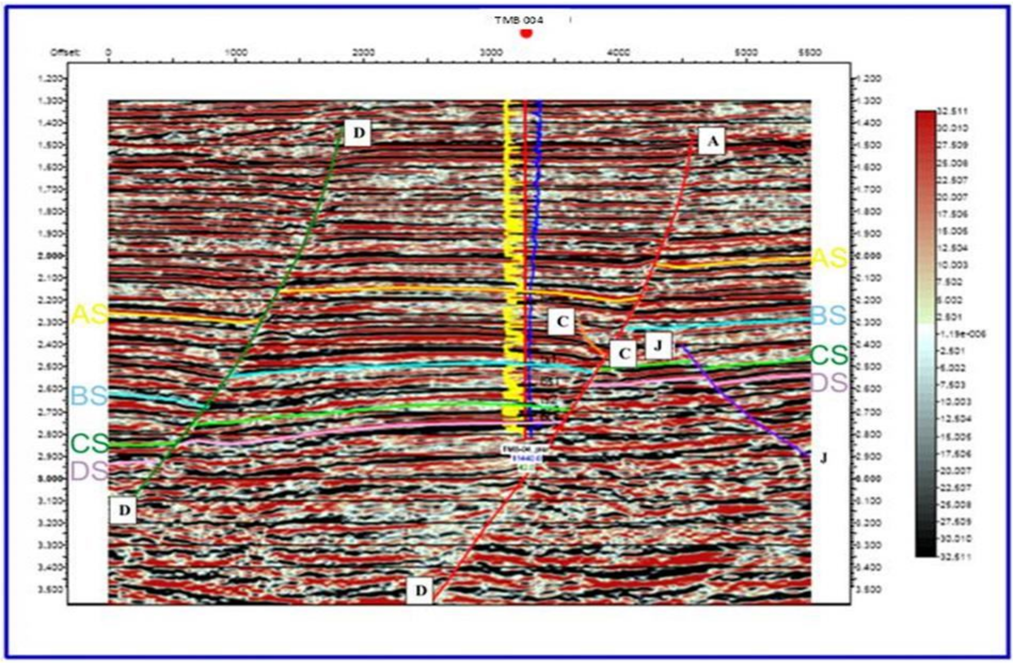
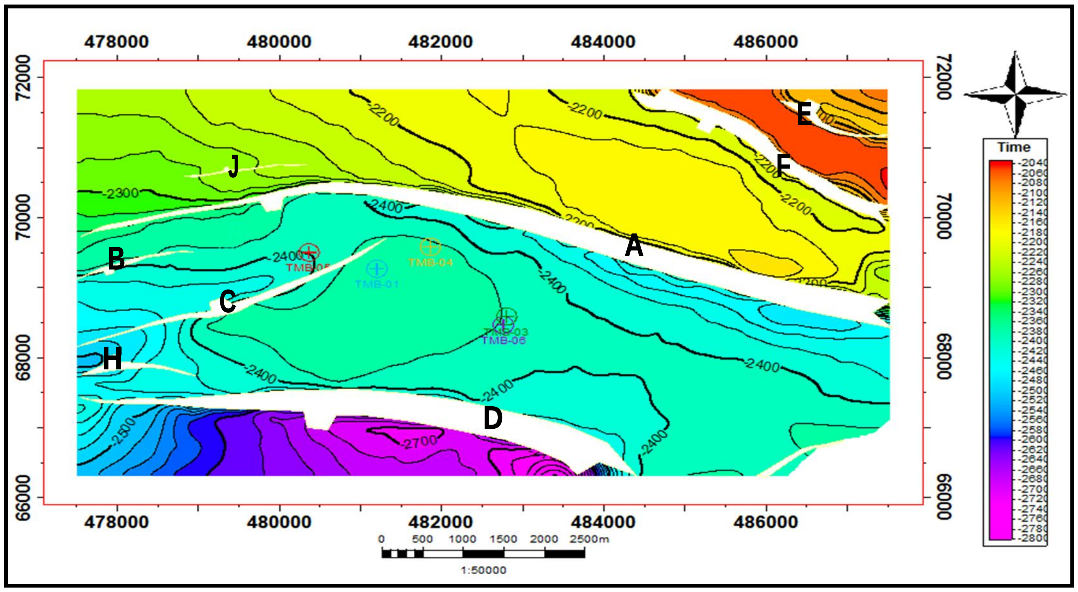
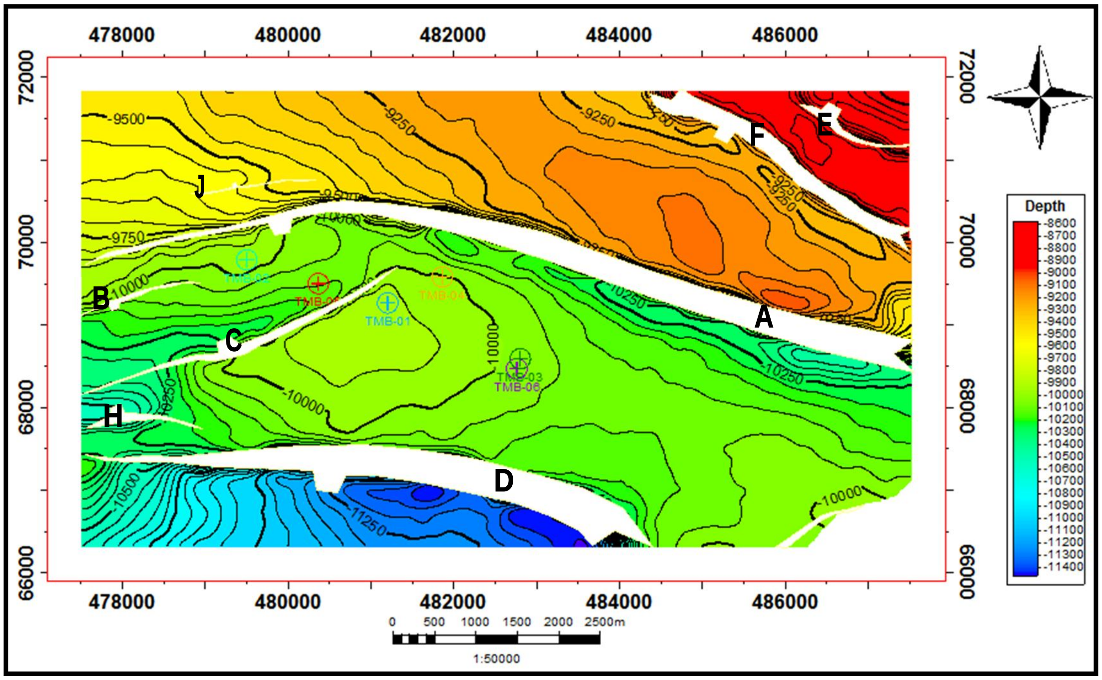


Figure 7: Inline 5925 with TMB 004, mapped faults and horizons (IHS Kingdom Advanced)

Figure 7 depict a South – North seismic section, line 5925 indicating some mapped faults and horizons. The faults mapped have curved; concave-upward fault planes in down dip direction. Figures 8a and b show the time and associated depth structural maps of OLA 1000 sand which reveals the fault frame work of the study area. The depth structure map (Figure 8b) reveals the trapping mechanism in the field to be fault-dependent. The trap is a fault closure against high and low structures on the upthrown fault block of fault D (a Northeast-Southwest trending antithetic fault), and the downthrown block of the main structure building Northwest-Southeast trending growth fault (A). The OLA 1000 sand was interpreted as thin sand (based on its average thickness of 28 ms) in the study area and thus subjected to further interpretation to verify the sealing capacity of the faults to keep the hydrocarbon in place.



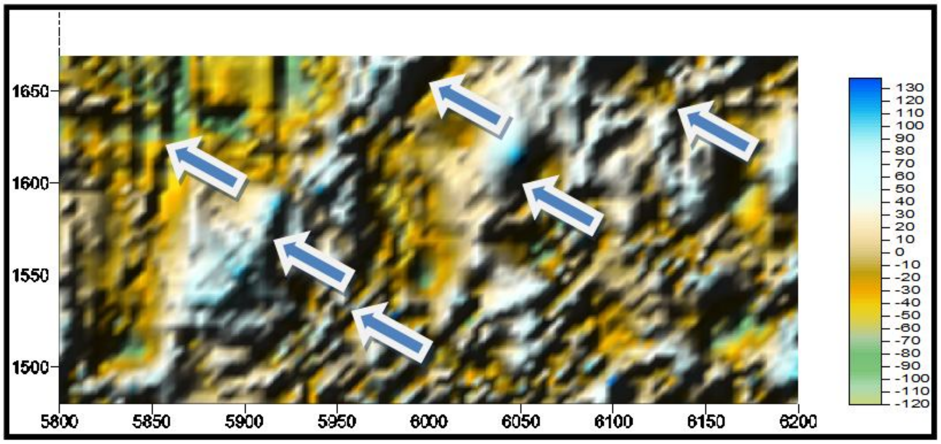
(a) Time Structure Map of OLA1000 Sand, “OLUMI” Field



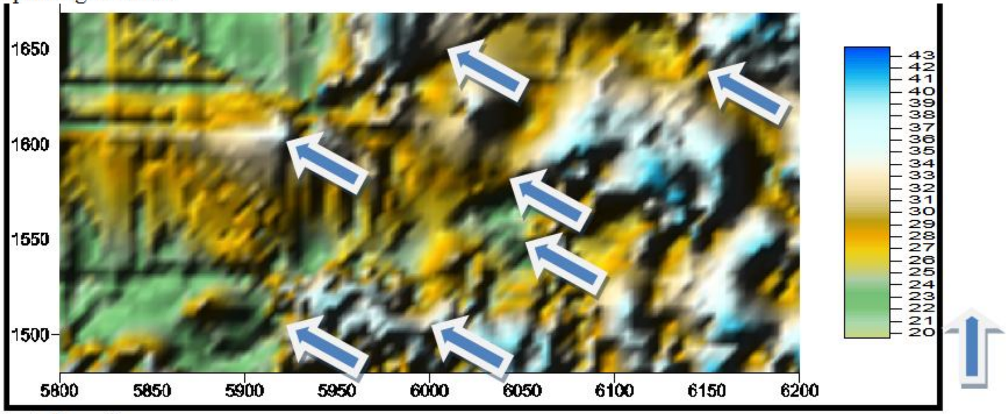
(b) Depth Structure map of OLA 1000 Sand, “Olumi” field

Figure 8: (a) Time and (b) Depth structural maps of OLA 1000 sand showing mapped faults A, B, C, D. E, F, G, H and I (IHS Kingdom Advanced).

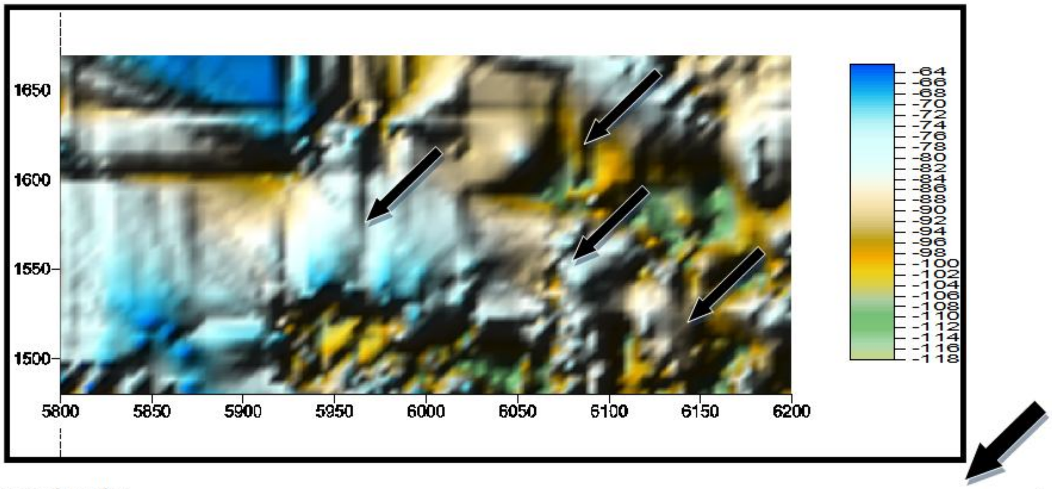
The Gamnitude and Quefrency maps (Figures 9a and b) revealed massive faulting and channelization occurring within the reservoir window thus establishing compartmentalization. The Saphe map (Figures 9c) and the 3-D Saphe plot (Figure 10) also show compartments within the reservoir sands which also have their sides lined by subtle micro faults. This could be the cause of the smear noticed along the fault lines on the amplitude section thus indicating the top seal of the reservoir may be ruptured.



(a) Cepstral gamnitude



(b) Cepstral quefrency



(c) Cepstral saphe.

Figure 9: Reservoir (OLA 1000) top (a) Cepstral gamnitude (b) Cepstral quefrency (c) Cepstral saphe. The arrows indicate faults occurring within the reservoir sands that are not ordinarily visible (OpendTect).

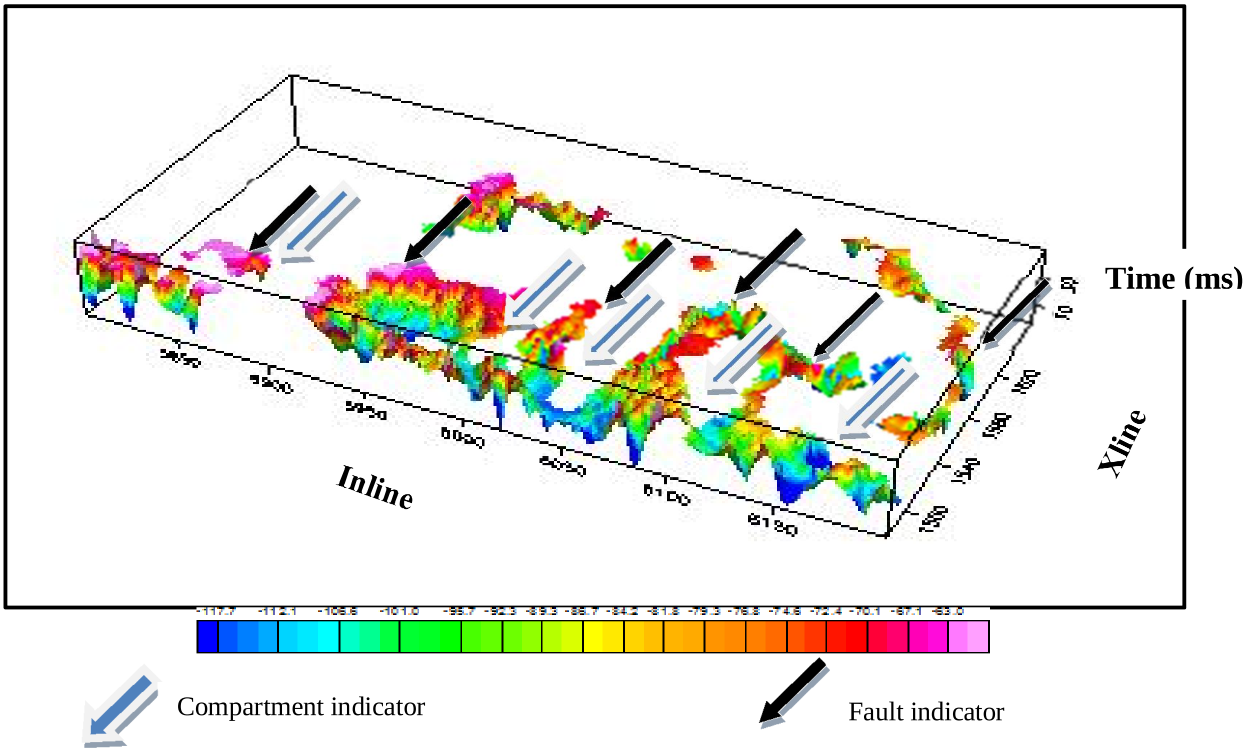


Figure 10: Reservoir (OLA 1000): Cepstra saphe filtered and plotted in 3D view. Compartments (indicated by blue arrows) within the reservoir sand, bounded by micro faults (indicated by black arrows) are apparent. This is suspected to be the reason for the smear noticed along the fault lines on the amplitude section thus indicating the top seal of the reservoir may be ruptured.

4. Conclusion

This study presents a novel workflow aimed at delineating subtle faults and indicators of fault sealing capacity and reservoir compartmentalization directly from seismic data. The workflow is based on cepstral decomposition to make valuable information that is not readily apparent from conventional interpretation available to the interpreter. Well and 3D seismic data were used to define both the structural and stratigraphic architecture of the study area. Validation of the results was made by computing the Cepstral attribute of a fault model. Given that the literature on the use of high resolution Cepstral techniques is limited; this new, non-conventional approach will reduce the exploration problems of detecting hidden and bypassed reservoirs and better delimit reservoirs. This will facilitate more hydrocarbon recovery, thus, enhancing field development.

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