Enhanced hydrocarbon recovery using the application of seismic attributes in fault detection and direct hydrocarbon indicator in Tomboy Field, western-offshore Niger Delta Basin

ABSTRACT

Seismic attribute analysis is important in subsurface data interpretation, such as seismic interpretation, which could involve seismic stratigraphic and structural interpretation. This interpretation is often hampered by seismic resolution and, sometimes, human inability to identify a subtle feature on the seismic. These factors have frequently led to the poor seismic interpretation of geologic features. Thus, an integral approach to studying structural patterns and hydrocarbon bearing zones using seismic attributes was carried out on the Tomboy field using 3D seismic data covering approximately 56 km^2 of the western belt of the Niger Delta. The seismic volume underwent post-stack processing, which enhanced seismic discontinuities. A deep steering volume was first created, and several dip filters were applied to enhance faults in the study area. After that, curvature and similarity attributes were calculated on the dip-steered and fault-enhanced volume. These calculations show detailed geometry of the faults and zones of subtle lineaments. Six faults (F1, F2, F3, F4, F5 and F6) were identified and mapped. These faults range from antithetic to crest growth faults. Two major growth faults (F5 and F6) were revealed to dip in the northeast to southwest directions. A near-extensive crest fault (F4) appeared beneath the major faults. Although several minor fractures were displayed in the southern and central portions of the crest fault of the dipping seismic data, the southwest (F4) and growth fault, F6, are responsible for holding the hydrocarbon found within the identified closures. Using attributes on the seismic data increased confidence in mapping and interpreting structural features. Furthermore, energy attributes were used as Direct Hydrocarbon Indicators (DHI) to visualize viable areas within the study, which allows a more robust interpretation. Time slices were taken in regions of flat and bright spots. The spectral decomposition attribute was run on these slices to display areas of high amplitude reflection typical of hydrocarbon-bearing regions trapped mainly by regional to sub-regional growth faults. The surface attribute calculated on the generated surface shows that the field is predominantly controlled by faults serving as traps for hydrocarbon.

Keywords: Seismic attributes, hydrocarbon, faults, bright spots, Dip filter

1. INTRODUCTION

The seismic attributes used in studies are suggested to be all the information obtained from seismic data, either by direct measurements or logical or experience-based reasoning (Taner, 2001; Thapar, 2004). Chopra and Marfurt (2005) defined seismic attributes as any information derived from seismic data, such as interval velocity, inversion for acoustic impedance (Aniwetalu et al., 2018), prediction of pore pressure (Joshua et al., 2022), and reflector terminations. Seismic attribute analysis has been vital in seismic interpretation since 1930 when geophysicists discovered the first seismic section. Since more than 50 attributes of seismic data have been obtained, more attributes have been found with advanced computer technology. For reservoir characterisation (Lunina et al., 2014; Shang et al., 2022;

Nwaezeapu et al., 2018; Oguadinma et al., 2023) and seismic interpretations (; Oguadinma et al., 2017; Oguadinma et al., 2018), seismic attributes analysis has been used by many authors (Vetrici and Stewart, 1996; Strecker et al., 2004; Ajisafe and Ako, 2013; Oguadinma et al., 2016; Oguadinma et al., 2021). It also proved its importance in the classification of the depositional environment (Ahmad and Rowel, 2013; Matos and Marfurt, 2013; Oguadinma et al., 2014) and in the detection and improvement of fractures and faults (Ayolabi and Adigun, 2013; Castillo, 2010; Francelino and Antunes, 2013; Santosh et al., 2013) to give details of structural history and provide direct hydrocarbon indicator (Adepoju et al., 2013). The seismic attribute technique is often used in seismic data processing because it can improve geological information not observed using the conventional processing method (Ayolabi and Adigun, 2013). Chopra (2002) used similarity as a coherence attribute in detecting trace discontinuities of the seismic data to detect faults and stratigraphic features. The curvature attribute is used in 3D horizon interpretation to characterise faults and fracture systems (Robert, 2001). In 3D seismic data volume, fault dipping can be detected using a semblance-based coherency algorithm (Marfurt et al., 1998, 1999). The study of Jones and Roden (2012) used the seismic attribute technique of dips of maximum similarity and curvature types to investigate the fault system of the South Texas oil field. Their study showed that the geometry seismic attribute technique helped to enhance and detect faults and fractures. At the same time, the curvature attributes were also applied to highlight other features not revealed by the geometry attributes application. This article aims to enhance fault visualization and highlight viable hydrocarbon placement using seismic attributes in the study area in the Niger Delta Basin.

2. GEOLOGICAL BACKGROUND

The Tomboy field is located in the offshore western Niger Delta Basin (Fig. 1). This basin is situated in the Gulf of Guinea, Central Africa. It lies between latitudes 4 ° and 6 ° N and longitudes 3 ° and 9 ° E. The tectonic framework of the Niger Delta margin along the western coast has been documented to be controlled by Cretaceous fracture zones that appear as ridges and sometimes trenches in the deep part of the Atlantic Ocean (Lehner and Ruiter, 1977). A regressive sequence where the sediment supply is higher than the subsidence rate (Reijers, 2011) causes the accumulation of clastic wedges approximately 12 km thick in the basin.

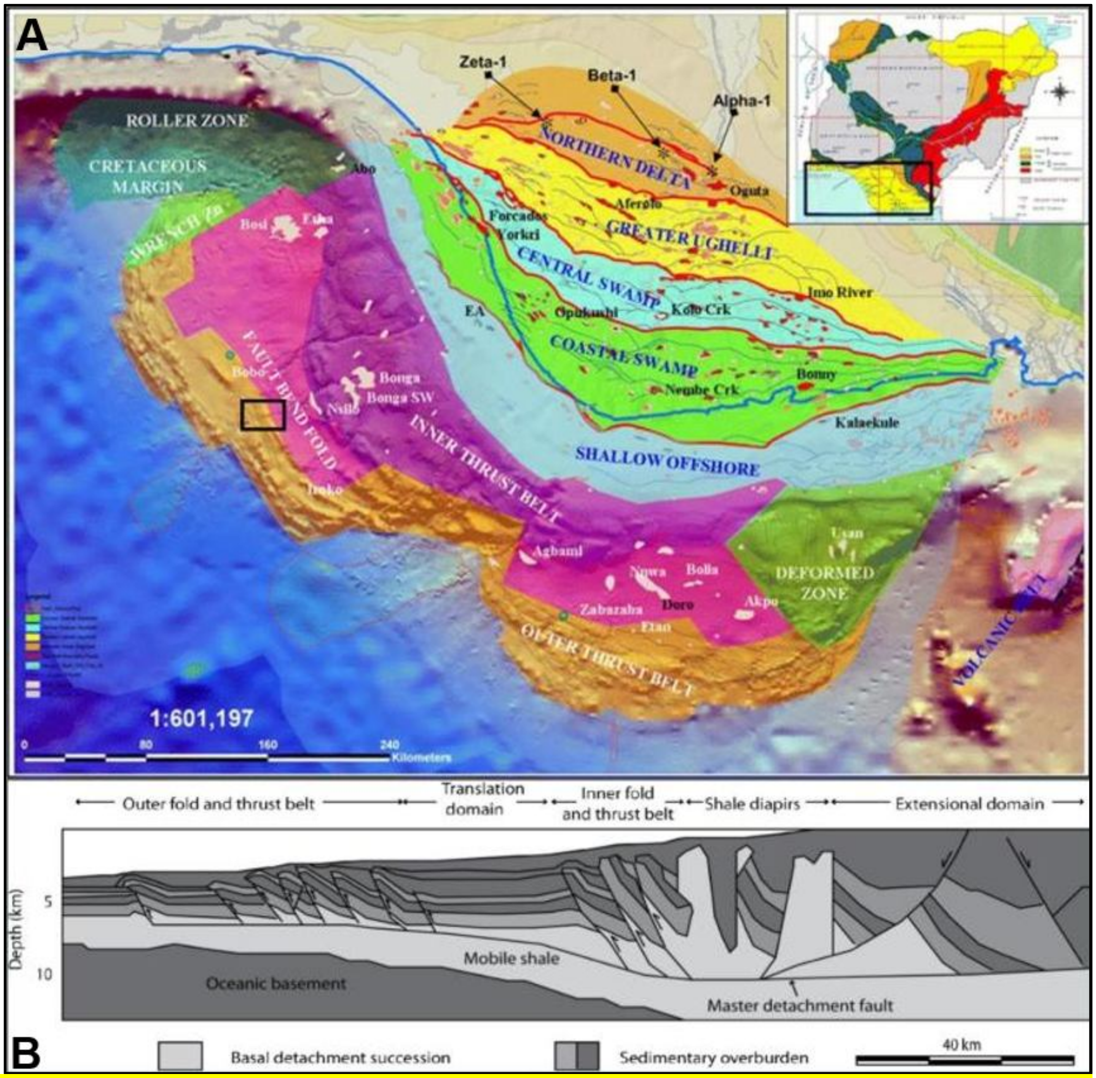

Fig. 1. (a) The Niger Delta complex shows different depocenters and the location of the studied area in a black box (modified from Ejedawe et al., 2002). (b) Cross-section through the Niger Delta shows the gross architecture and structural style typical of large deltas on passive margins (Corredor et al., 2005).

In the delta, shale tectonic activities are on the rise (Oguadinma et al., 2021). For example, shale mobility induced internal deformation in response to some processes. One of the processes is shale diapirism formed from loading poorly compacted and overpressure prodelta and delta slope clay (Agbada Formation; Tuttle et al., 1999) by high-density delta front sands of the Agbada Formation. Another process is slope instability due to a lack of lateral basin-ward support for the under-compacted delta-slope clay (Akata Formation). The Benin Formation is Oligocene and younger. It comprises continental floodplain sands and alluvial deposits with deposits estimated to be 2 km thick (Tuttle et al., 2015). The stratigraphic column of the lithostratigraphic units of the Niger Delta is shown in Fig. 2.

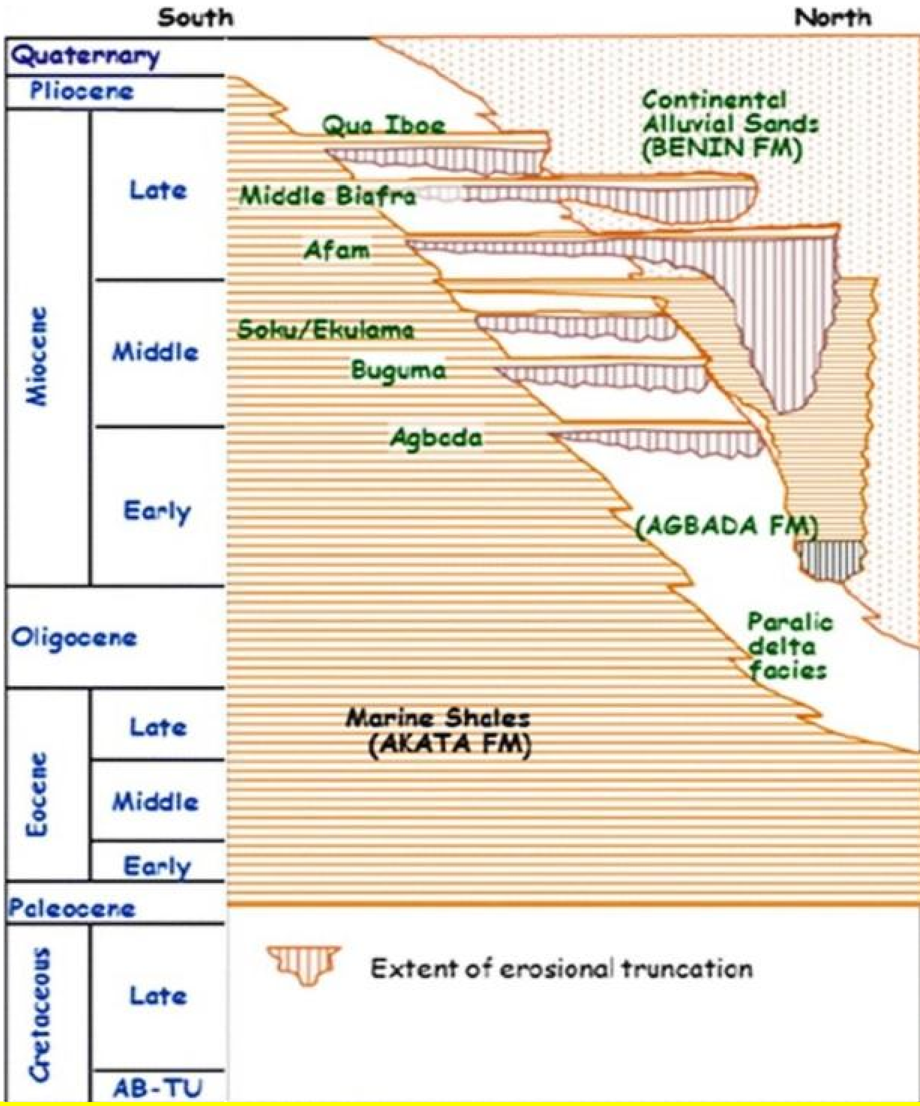

Fig. 2. Regional stratigraphy of the Niger Delta showing different geologic formations (Akata Formation, which is the oldest; Agbada Formation that overlies the Akata and the youngest Benin Formation containing mainly alluvial deposits) (Ozumba, 2013)

3. METHODOLOGY

This study used 3D seismic data loaded into the OpendTect and Petrel interpretative software. The data was scanned and realised to improve the signal-to-noise ratio and decrease the data size to enhance data processing and interpretation. Data were quality checked for errors, and corrections were made. The fault mapping was done manually on the inline and crossline sections. The seismic data was steered for a more detailed interpretation, and the objective was to improve the signal-to-noise ratio for better seismic data to run interpretations on.

Seismic attributes such as curvature, semblance, energy, and spectral decomposition were used for fault detection and DHI. The similarity attribute has been defined as the Euclidean distance between the normalized vectors over the vector lengths. Similarities of one and zero indicate that the trace segments are identical and nonidentical, respectively (Tingdahl and De Groot, 2003). Using the OpendTect software window environment, it is observed that the calculation of similarity is often favoured by determining the direction of the best match at every position, which is a result by itself: the dip. Applying the similarity attribute is relatively easy and provides clarity at every stage. When integrated with other attributes, this attribute would certainly give impressive results in the shortest possible time.

The spectrum decomposition and the semblance attributes maps are based on "horizons" (+/- a few metres around the interpreted horizons). The spectral decomposition RGB frequencies of the blending used were from frequency evaluation of the interval of interest of the seismic data using the work of Peyton et al. (1998). The semblance attribute stresses seismic trace-by-trace and utilizes observations and interpretations of structural and stratigraphic features.

Different steering cubes were calculated from a different algorithm. From Fig. 3, subtle features in the full stack steering cube were visible after the background steering cube was calculated (Fig. 3c). This region is circled in red. To explain further, dip steering is used when seismic reflectors are followed by auto-tracking the pre-calculated dip field from any starting position. Working with more than a steering cube is essential hence the three steering cubes in this study: the Full steering cube, the Detailed steering cube and the Background steering cube (Fig. 3a, 3b and 3c, respectively).

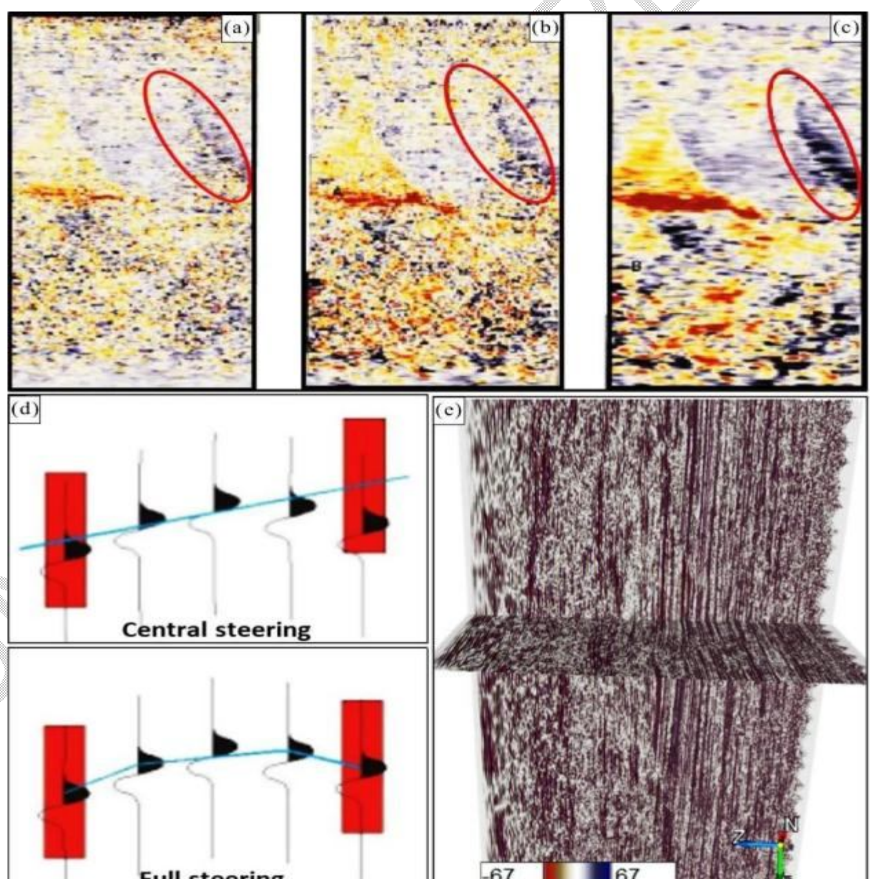

Fig. 3. (a) Full-stack steering cube, (b) Detailed steering cube and (c) background steering cube. Notice how the fault on the full stack steering cube was enhanced at the background steered cube. (d) Comparison between central and full steering cubes. It appears that the relationship in the full steering cube is better than the centre, while the detailed and background steering is

better than the full steering cube. (e) Inline and cross-line sections were obtained from the data. The red box represents the location of the study area.

In OpendTect, data-driven steering is of two types: Central and full steering (Fig. 3d). Where a trace segment follows the central steering dip/azimuth at the point of evaluation point to compute filters and seismic trace at an event, the full steering, at every tract position, is updated. The detailed steering cube (Fig. 3b) is made of dips calculated from the dip computation algorithm and is used to preserve details in the data (Fig. 3 and Table 1). For example, in a fracture detection study. On the other hand, the Background steering cube is (Fig. 3c) usually median filtered and a smoothed version of the Detailed steering cube (Fig. 3b). If well-filtered, it contains less noise; notably, the dips follow larger structural trends.

Table 1 Setting of seismic attributes with a dip-steered attribute, step-out, statistical operator, and time gate values.

Attribute	Dip-steering	Step-out	Statistical operator	Time gate (ms)
Similarity	Not steered	N/A	Minimum	(-24, 24)
Curvature	Steered	(1, 1, 1)	Maximum	(-24, 24)
Raw steering	N/A	(1, 1, 1)	N/A	N/A
Detailed steering	N/A	(1, 1, 3)	N/A	N/A
Background steering	N/A	(5, 5, 0)	N/A	N/A

4. RESULTS AND DISCUSSION

4.1 Interpretation of faults

The structural framework was carried out by picking assigned fault segments on inline 5860, 5884 and 5980 sections of the seismic volume (Figs. 4 and 5).

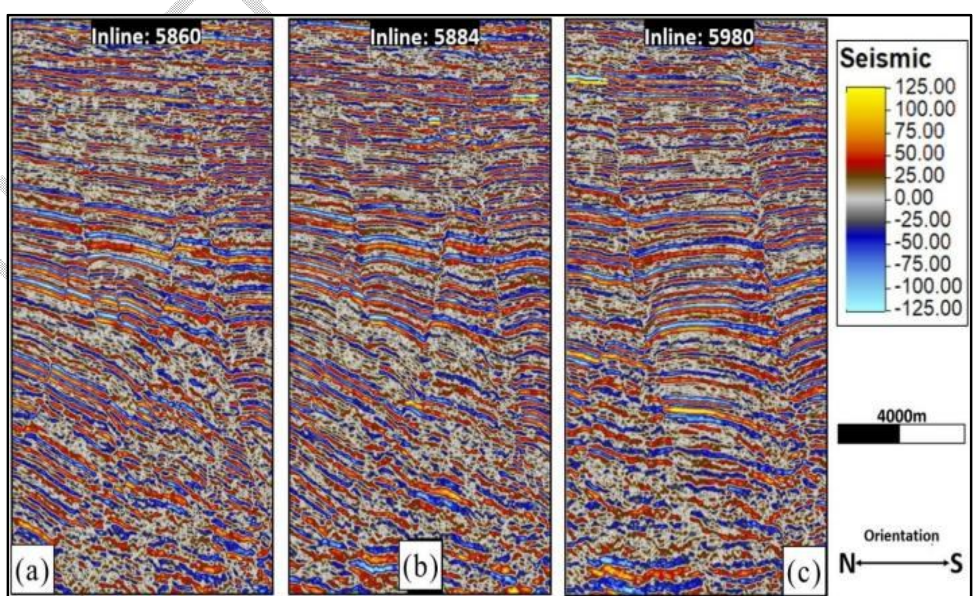

Fig. 4. Uninterpreted seismic sections of inlines 5860, 5884, and 5980. Notice the map's legend, scale, and orientation on the right-hand side of the figure.

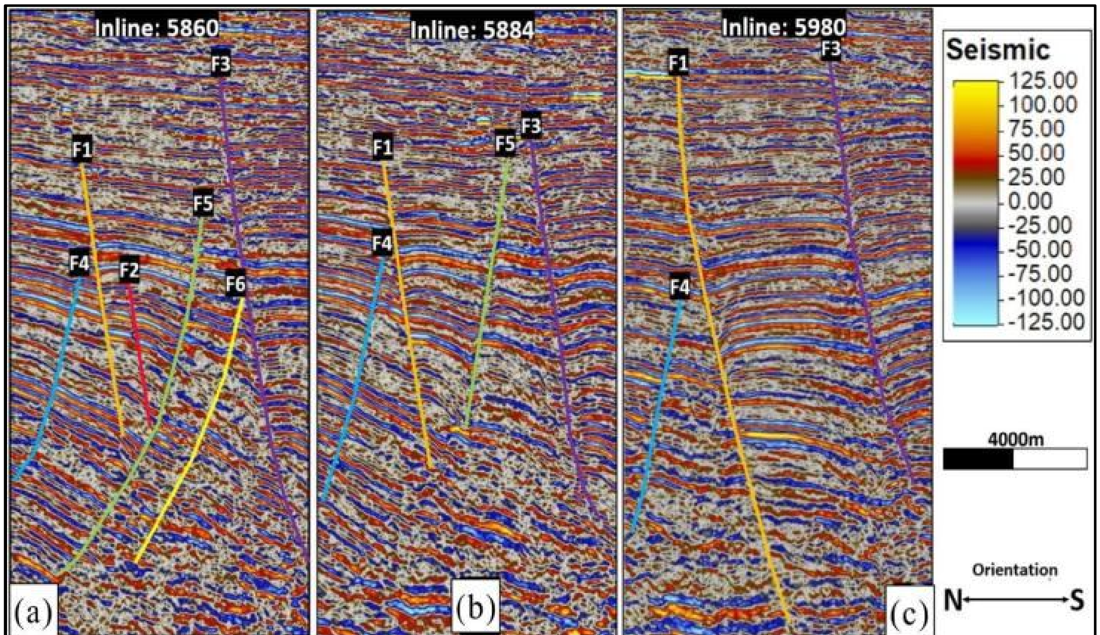

Fig. 5. Interpreted seismic sections of in-lines 5860, 5884, and 5980. Six faults were observed and interpreted in seismic sections A, B and C.

These identified and interpreted faults in the seismic sections were due to discontinuous reflection along the disorientation of reflectors or as distortion caused by an anomaly of the amplitude around the fault zones (Ning et al., 2022). A total of six faults noted as F1, F2, F3, F4, F5 and F6 were identified on the inline sections (Figs. 4 and 5; Table 2). Some of these faults extend through the extent of the field, known as major regional growth faults and some antithetic faults (Table 2). The four growth faults, F1, F3, F5, and F6, are dipping southward, while others dip toward the north except for the minor fault (F2) dipping southwest.

Table 2 Interpreted faults along the inline sections of the entire 3-D seismic volume noting fault type, dip direction, and fault symbols

Fault Type	Dip Direction	Fault Symbol
F1	Southwest	Minor Growth Fault
F2	Southwest	Minor Fault
F3	Southwest	Major Regional Growth Fault
F4	North	Antithetic Fault
F5	Southeast	Major Growth Fault

F6	Northeast	Major Growth Fault

4.2. Attribute Analysis and its significance

Different attributes (i.e., similarity, spectral decomposition, energy, and diffusion filter; Table 1) were run on the seismic cube. Z-slices were taken on the original seismic and displayed as flattened maps. Structures respond to acoustic waves differently; thus, the attributes extracted are best used to study different subtle and sub-seismic faults missed by conventional seismic interpretation. Figs. 6 and 7 show the results of similarity attributes applied to the data used for this study and the clarity of structural features it provides. It made subtle features visible and interpretation easy while increasing the results' confidence (Fig. 7). Observe the uninterpreted maps from seismic lines 5884 and 5980.

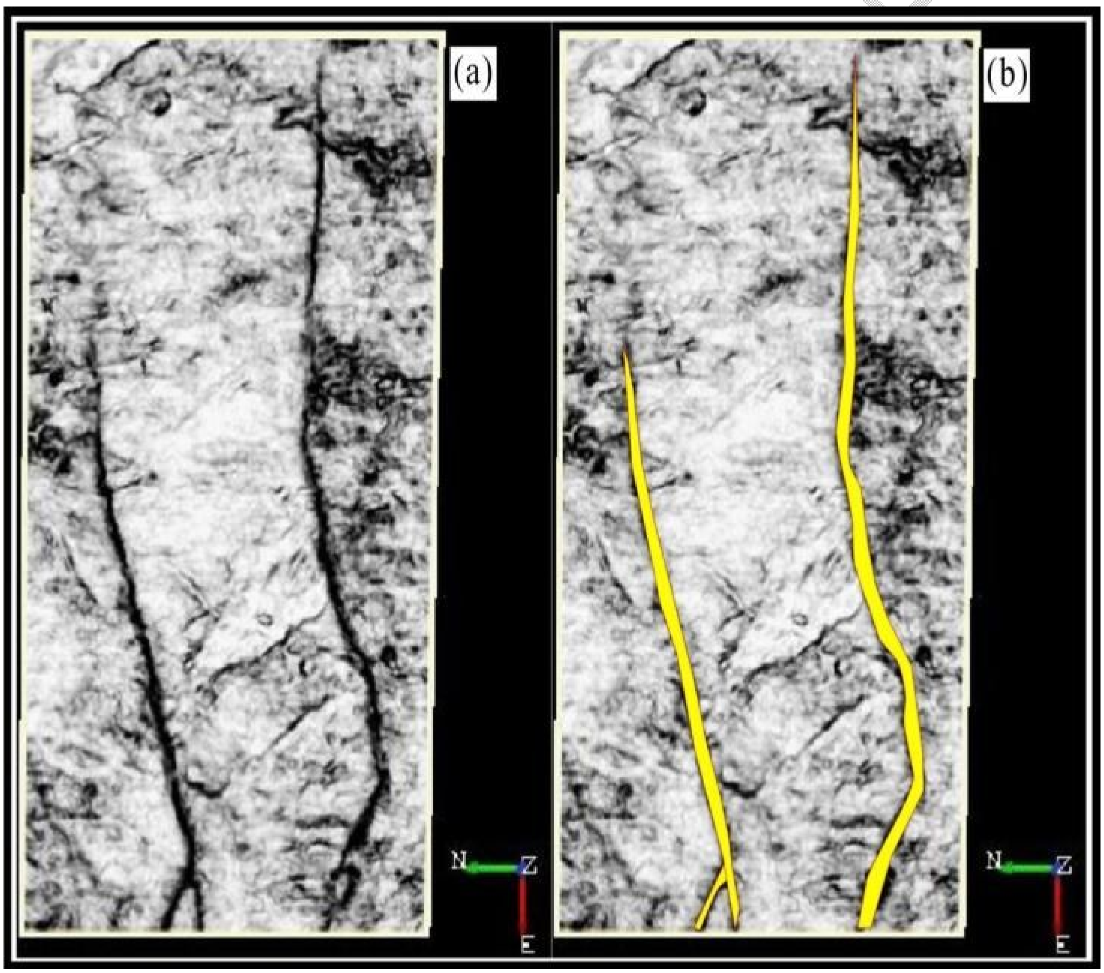

Fig. 6. Extracted similarity attribute slice around inline 5860. (a) shows the uninterpreted map with regions of possible discontinuous reflections. (b) shows the same map as the interpreted faults.

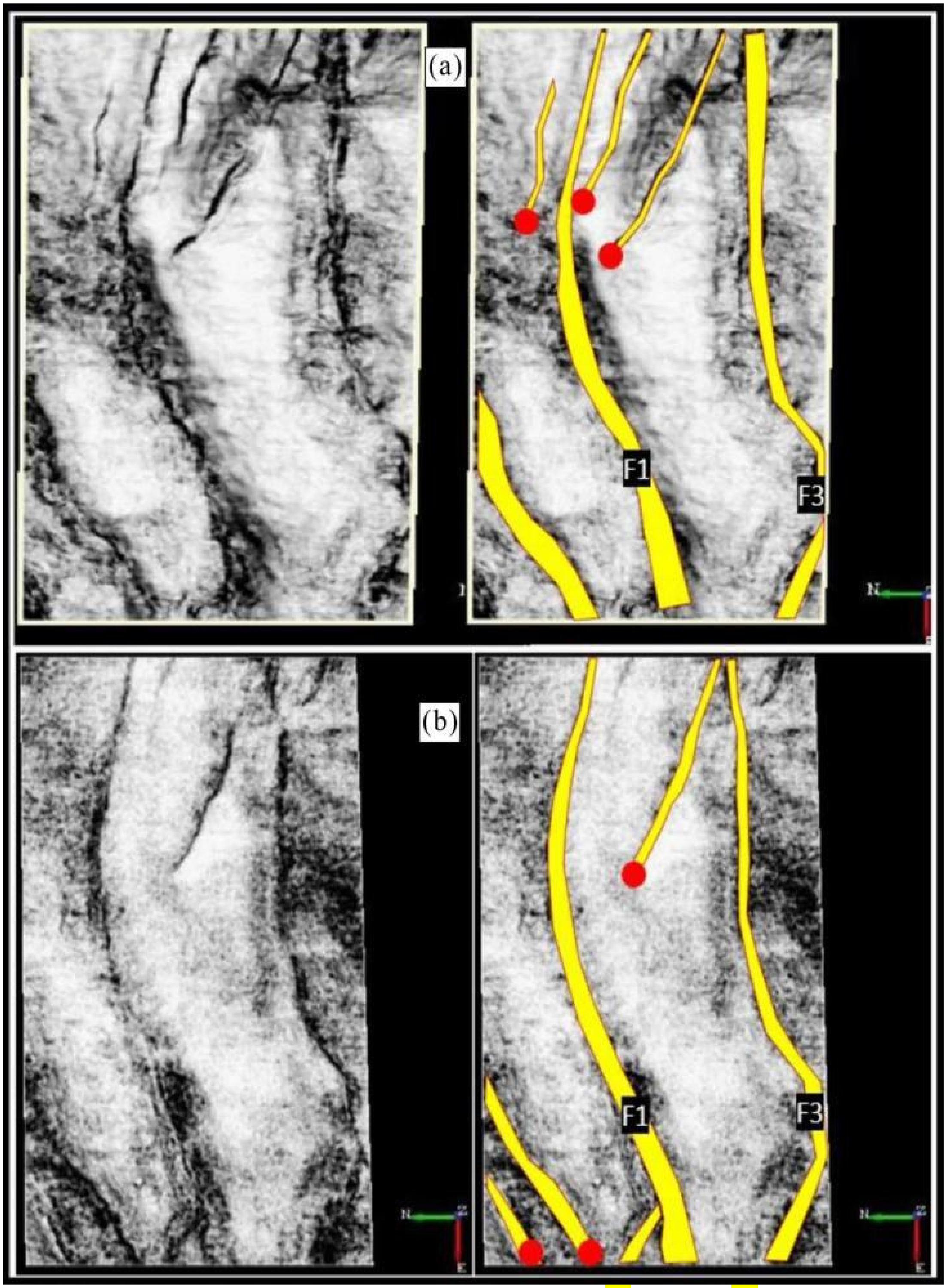

Fig. 7. Extracted similarity attribute slices around inline 5884 (a) and 5980 (b). The uninterpreted maps showing regions of possible discontinuous reflections are on the left of both (a) and (b). On the right are the same maps with the interpreted faults. F1 and F3 represent fault one and fault three, respectively. The red circles are placed in faults not identified on the seismic sections.

The energy attribute is the sum of amplitudes squared in a time gate. It highlights packages with different reflection strengths in seismic reflections (Fig. 8). In siliciclastic, energy attributes can decipher lithology and sediment porosity types and enhance bright spot regions. In this study, the application of energy attribute has made it possible to identify bright spots on the time slices obtained from the seismic volume (see Figs. 8b and 9), serving as a pre-plan methodology for highlighting possible hydrocarbon regions for good interpretation decisions even without the presence of well logs like gamma-ray and resistivity to help identify and classify reservoir bearing formations (Oguadinma et al., 2021). Hence, its usefulness cannot be overemphasized. The application of energy attributes is not universally known, and most researchers and industry experts are oblivious to its use. This is because applying root mean square attribute and spectral decomposition serves similar purposes. However, from the quality of the results generated in this study, the energy attribute has proven to be an even better direct hydrocarbon indicator (DHI) tool for effectively identifying leads and hydrocarbon prospective regions.

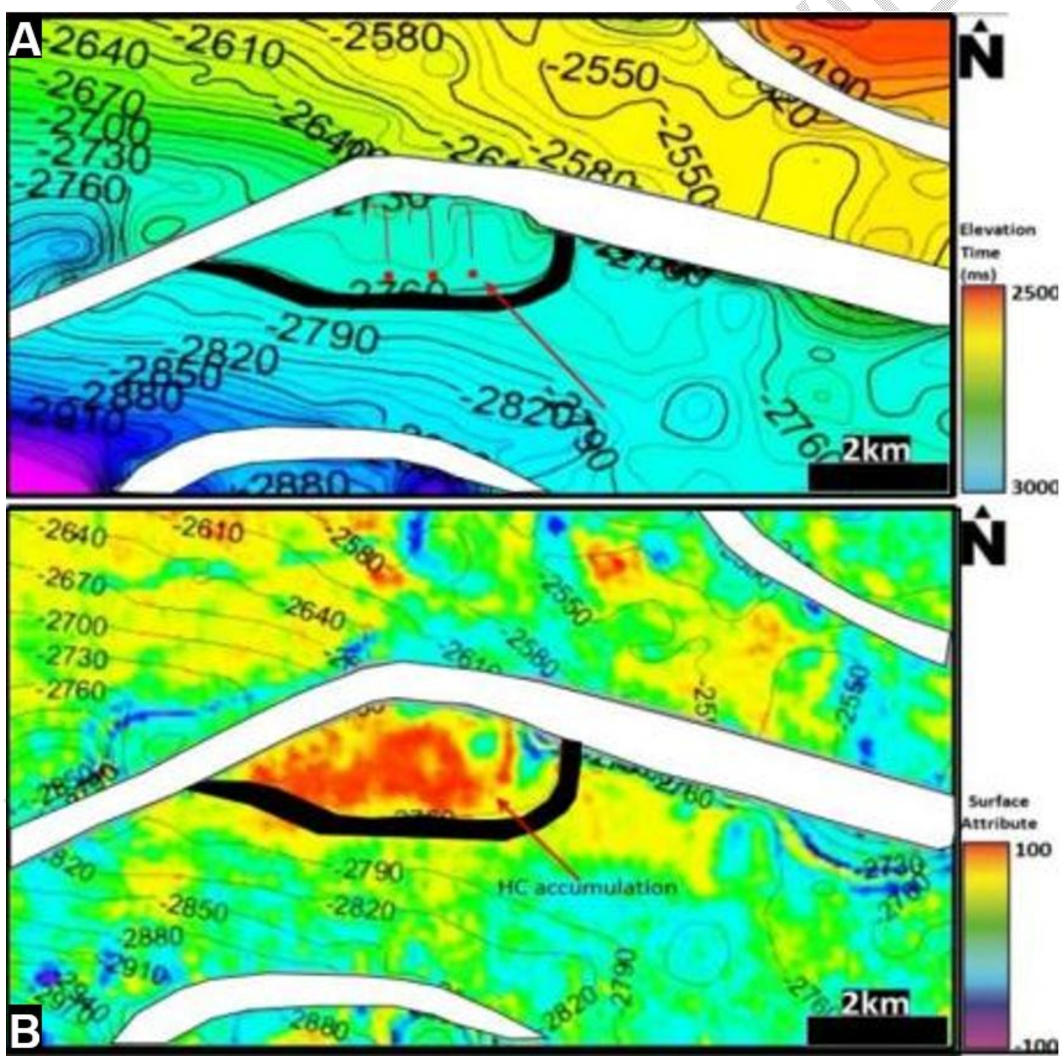

Fig. 8. (a) Interpreted time surface map of a horizon mapped at 2748 showing faults. (b) Contour 2760 is closing on a major fault. The hydrocarbon-containing region was evident on this attribute map in contour 2760 of the surface map in (a). HC stands for hydrocarbon accumulation

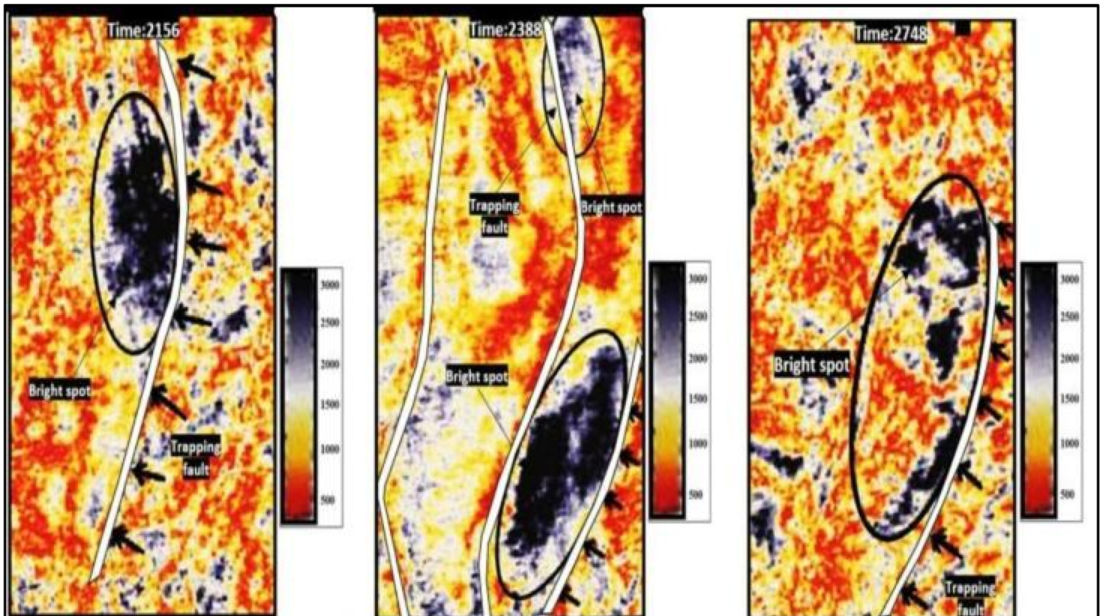

Fig. 9. Time slices showing areas of high-amplitude anomalies observed at times 2156, 2388 and 2748, respectively. Using energy attributes, these areas are interpreted as bright spots (potential hydrocarbon areas), and hydrocarbon accumulation was observed to close on faults.

Using the spectral decomposition attribute, the effect of frequency assessment was carried out on the seismic data obtained from the Tomboy field. Observations were made to confirm the viability of the energy attribute application and to ground truth the finding about the field having places of bright spots (Fig. 10b). First, a horizon was interpreted in both the inline and the crossline sections across the entire 3D seismic volume. The interpreted horizon is converted into a time surface map before applying the spectral decomposition attribute (Welsh et al., 2008). The spectral RGB (red, green, and Blue) frequencies were fine-tuned to agree with the layer of the horizon that it is to be applied. This action helped manage the frequency difference until the desired output map was clear enough for interpretation. Fig. 10a shows a time surface map from time 2388, and Fig. 10b shows the result of the spectral decomposition attribute extracted from the horizon. Notice the abnormally high-frequency reading in the red circle bounded by two faults.

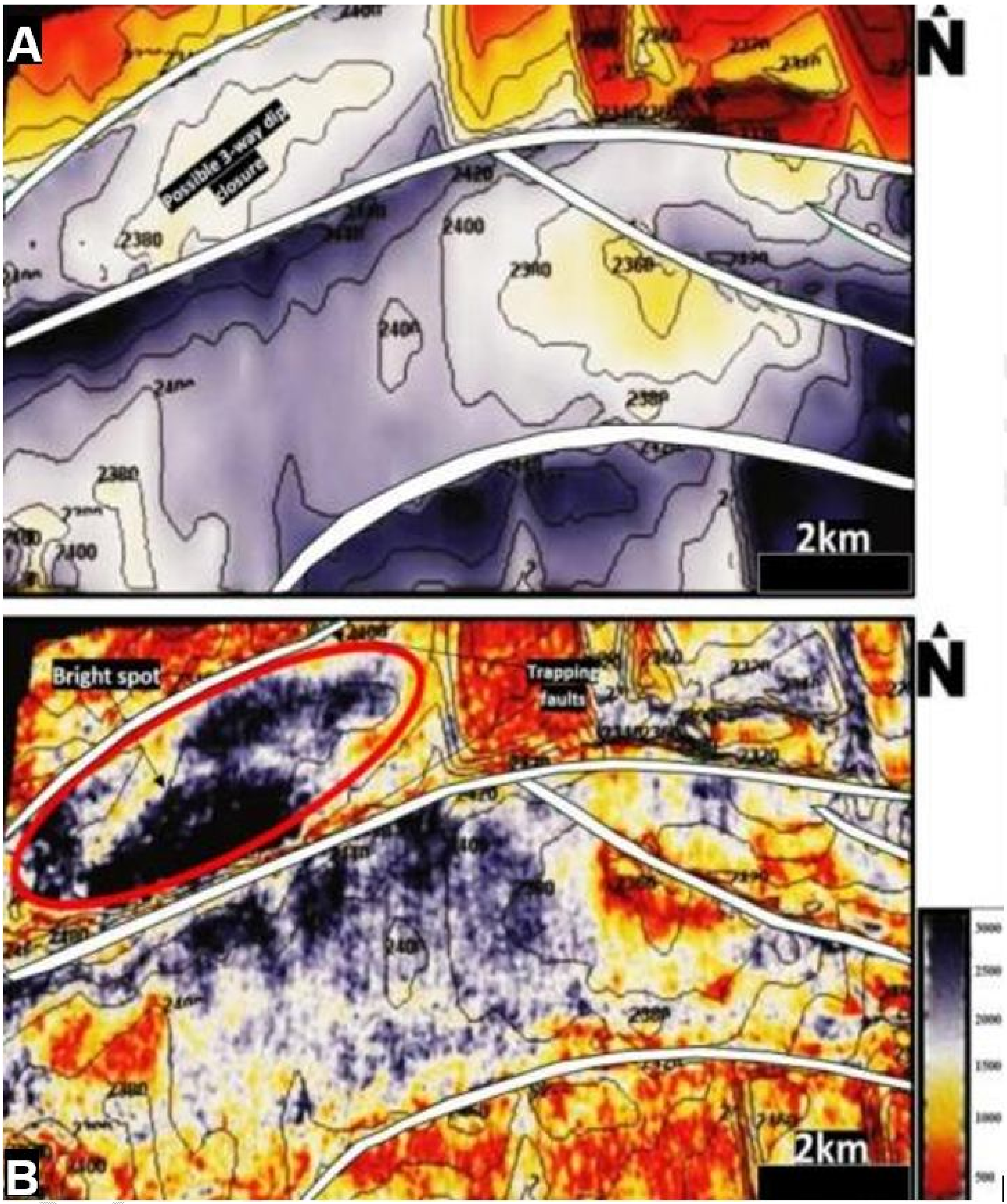

Fig. 10. (a) Time surface map of a horizon mapped at time 2388 with a series of faults dipping in the SW-NE direction. (b) The spectral decomposition map was extracted from the OpendTect software. It shows a bright spot region enclosed in a red circle, closing against faults.

5. CONCLUSION

A similarity attribute is an excellent tool for improving structural interpretation. It plays a crucial role in subtle feature detections not usually detected by human eyes or subtle features beyond seismic resolution. These seismic attributes are better applied on the horizon and time slices. However, it is advised that data quality checking and signal-to-noise ratio be applied before running the attribute method on the data. This will guarantee a better output of the expected results of the data. Interpretation of the 3D seismic data for locating both seismic scales and sub-seismic scale structural elements and areas of possible hydrocarbon accumulation has been demonstrated to be more efficient using seismic attribute mapping and analysis. From this study, several observations have been made.

- ★ Seismic attributes can be run on an entire 3D seismic volume before interpretation begins.
- ★ Seismic attributes extracted from time slices are essential and can be used as reconnaissance for better visualisation of areas to focus on during a detailed interpretation.
- ★ Spectral decomposition and energy attributes have proven very useful as direct hydrocarbon indicators by identifying bright spot areas that are interpreted to contain a significant amount of hydrocarbon.
- ★ It was also observed that fault block displacement leads to seismic reflection discontinuity. By identifying and interpreting faults in the data, displaced seismic reflections can be better correlated from one fault block to the other. This will improve interpretation confidence and produce a better result.

Integrated discontinuous attributes and other seismic attributes would yield better hydrocarbon exploration outcomes. Therefore, seismic attribute analysis should be integrated into the standard practice of hydrocarbon exploration and production; and oil companies can quickly reduce the risk of drilling dry holes resulting from missed faults due to conventional seismic interpretation methods.

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