**ORIGINAL PAPER-EXPLORATION GEOLOGY**

# Decoding of seismic data for complex stratigraphic traps revealing by seismic attributes analogy in Yidma/Alamein concession area Western Desert, Egypt

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## Abstract

Sandstone channels are one of the best stratigraphic traps for hydrocarbon accumulation, and their depositional and composition make them difficult to detect on ordinary seismic data, especially in structurally affected onshore areas like the Western Desert of Egypt. The Western Desert of Egypt has many hydrocarbon-bearing reservoirs of various compositions like carbonates and sandstones with high production rates, and thus the Western Desert of Egypt is recognized as a hot spot for oil and gas exploration. One of the important reservoirs in the Lower Cretaceous "the Aptian sand" produced around 285 MBBLS cumulative oil of 22° API and still produces 102 BOPD. This reservoir has a channel-type depositional environment, and the dimensions of this channel could be resolved by good quality 3D seismic data in the moderately deep basins as the basins become deeper, the detection of the channel becomes increasingly challenging. This study aims to delineate the geometry of this reservoir and reveal the exposure from the Aptian sand channel in the Alamein area using the seismic attributes analogy on the re-processed 3D seismic data to determine the best drilling location for increasing the production from this reservoir. In this context, the relative acoustic impedance (RAI), iso-frequency components, and sweetness stratigraphic attribute analyses were conducted on the optimized seismic data and attested as important as they resolved the stratigraphic geological mystery in the structurally affected study area. These attribute analyses revealed the exposure from the distinctive meander channel of the Aptian sand for the first time in the study area nearby the producing Alamein field, where this channel was hard to be distinguished by the ordinary seismic interpretation methods and there is no drilled well penetrated the detected channel's body. Upon the results, the conclusion and recommendation summaries to intensify the efforts to test the productivity of the detected channel to increase the production from this motivating reservoir by drilling a new well targeting the best structural locations of the channel body.

**Keywords** Sand channel · Seismic attributes · RMS amplitude · Yidma/Alamein concession · Egypt

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## Introduction

The Western Desert forms the largest geographic province of the country, covering about 700,000 km$^2$ or more than 2/3 of the whole area of Egypt. It is located between the Nile River and the Libyan Border with oil- and gas-producing concession areas like Yidma/Alamein concession area (Fig. 1). Recently, these concession areas ranked the Western Desert as the second priority for hydrocarbon production after the Mediterranean.

The Yidma/Alamein concession area has a thick sedimentary cover controlled by a variety of structural and stratigraphic elements, which form different types of structural and stratigraphic traps (Younes 2012). The most important reservoirs in the study area are the Lower Cretaceous
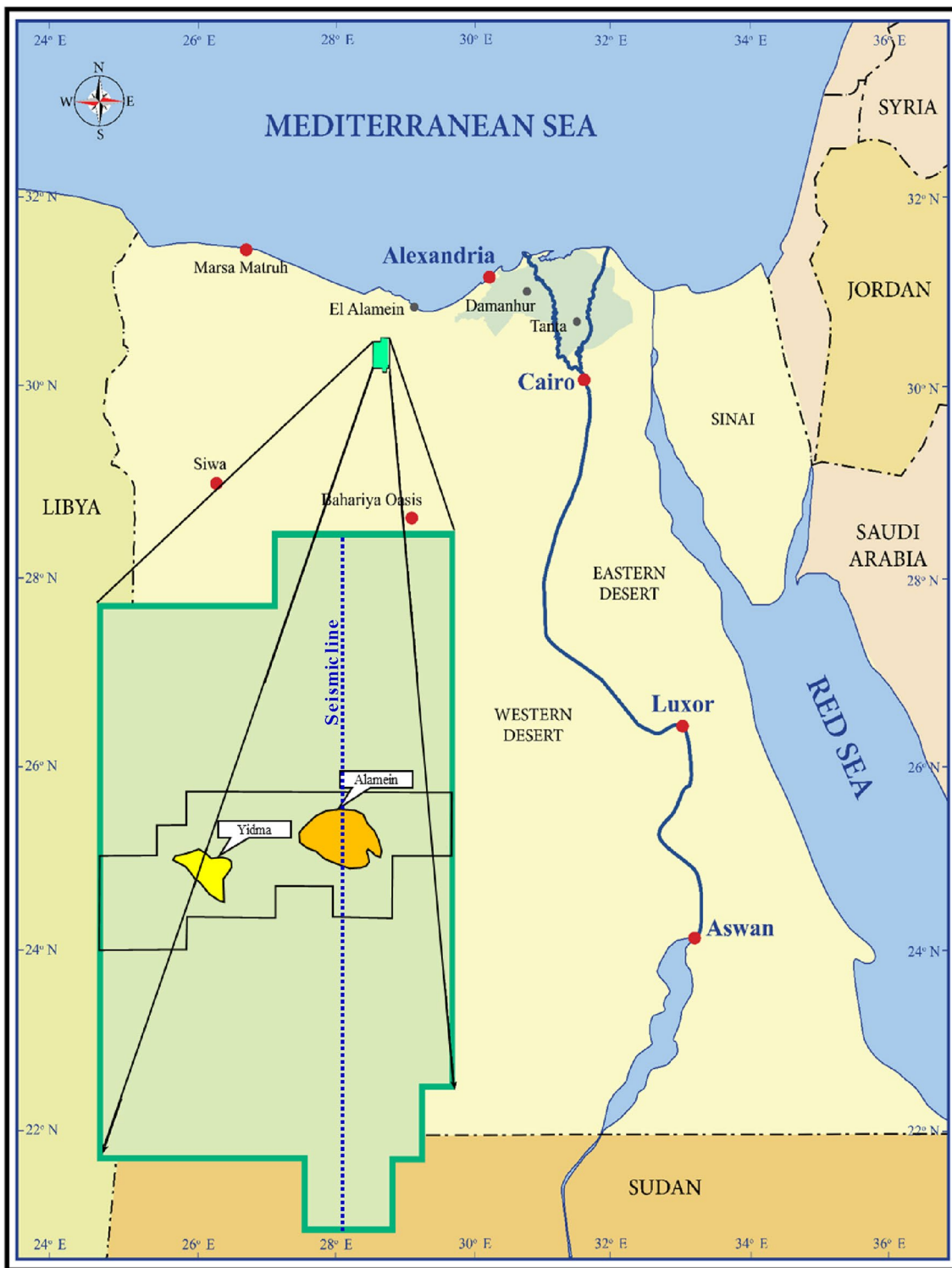
**Fig. 1** Location map of the Yidma/Alamein concession area showing the study area in the central part of the concession and the seismic line trending N–S direction

reservoirs, like the Aptian sand, having a channel-type depositional environment. The dimensions of these reservoirs can be resolved by good quality 3D seismic data in the moderately deep basins to about 10,000 ft depth. However, as the basins become deeper, the detection and definition of the dimensions and geometries of these channels become increasingly challenging, and the stratigraphic analysis of the seismic attributes reflecting the indicative response of

such geological features on the seismic data becomes highly beneficial for hydrocarbon exploration, (ElNikhely et al. 2015).

Seismic attributes are information obtained from quantitative analysis or measurements of the seismic data; these measurements are for the seismic anomalies of deformed waveforms on the geological interfaces. Generally, each seismic attribute has its own mathematical algorithm, and the analyses are computed by mathematical manipulation of the original seismic data, and hence they highlight specific geological, physical, or reservoir characteristics (Harishidayat et al. 2022). Accordingly, using the seismic attribute for stratigraphic analysis in the producing Alamein area helped in understanding types of deposition environments and delineating the Aptian sand channel geometry.

## Geological setting

All through the geological history, the stratigraphic sequence in the northern part of the Western Desert formed in various depositional environments, where the basins were shaped and deformed by the different tectonic orogenies to receive a sedimentary cover of thickness increase northwards to more than 30,000 ft.

Different phases of these tectonic orogenies affected the shape of the basins and deformed the sedimentary sequence; the first phase was the Caledonian Orogeny that occurred in the Middle Palaeozoic, the Hercynian Orogeny was at the end of the Palaeozoic, and the last phase was the Alpine Orogeny which transpired in Jurassic-Tertiary. The basins were oriented in various alignments controlled by the tectonics of each orogenic phase subsequently, and the central axes of these basins shifted continuously with basin development evidently in the sediments thickness variation in the region (Schlumberger 1995).

The northern part of the Western Desert formed a platform area of relatively gentle subsidence near the actively subsiding basins wherein the Paleozoic, most of the area lay to the east of the most active basin, occupies the Siwa-Kufra, Libya area (the Kufra Basin). During the Jurassic, substantial tilting shifted the center of the basin into the northeast of Egypt leaving parts of the Western Desert as a platform (Said 1990).

Generally, the sedimentary cover in the northern part of the Western Desert had been deposited in different environments (El Shazly 1978; Hantar 1990; Bayoumi 1996), and due to the variety of those environments, a wide variety of sediments (marine, continental, etc.) had been accumulated over billions of years from the Paleozoic to the most recent deposits on the surface (Abdine and Deibis 1972; Abdine 1974; Said 1990). The stratigraphic column in the study area "the Alamein area" (Fig. 2) comprises much of

the sedimentary succession from the Precambrian basement rocks to the recent deposits (Schlumberger 1994). The area is located in the Dahab-Mireir basin (Fig. 3); one of the series of elongated faulted basins is separated by high ridges and is the center of the coastal basins in the Western Desert. It had been deformed in Jurassic-Cretaceous times, where it extended along the northeast to the southeast part toward the Abu-Gharadig basin and the inter-basin area of Natrun and Gindi basins (Abdine and Deibis 1972; Abdine 1974; Barakat and Nooh 2017).

The gravity, magnetic, and seismic surveys indicated that the sedimentary cover increases northwards where the basin expansion formed a good accommodation space to receive over 25,000 ft of sediments before thins to 9800 ft over the Ras Qattara ridge to the north making the northern edge of the basin (Abd El Halim 1992). By the beginning of the Early Cretaceous, the basin center subsided more rapidly than the Alamein anticlinal area and shifted to the north to the present Mediterranean offshore area parallel to the present shoreline (EGPC 1992).

Structurally, Egypt can be regionally divided into the Hing Zone, the Unstable Shelf in the north, the Stable Shelf, and the Nubian/ Arabian Craton in the south, where Egypt lies in the northeast corner of the African plate which is made up of the basement of the East Sahara Craton and the Arabo-Nubian Shield. During the Mesozoic, the central portion of the Western Desert covers the transition zone between the Stable and Unstable Shelves (Schlumberger 1984; Abd El Halim 1992; Barakat 2010).

Numerous tectonic actions affected the northern part of the Western Desert, but the most important occurred during the Late Cretaceous and Early Tertiary probably due to the African plate movement toward Europe; it caused the folding trend ENE-WSW of the major portions in the north (Syrian arcing system). Most fold origin is caused by compressional movement while the others are the folds confined to fault blocks of normal or horizontal displacement. The northern portion structure is dominantly controlled by normal faults of displacement magnitudes of 750–3000 m, and some of these faults had strike-slip movements that affected the orientation of the fold axes (Said 1990).

The rifting in the study area started in the Jurassic and continued during the Cretaceous until the Early Senonian. During the Early Cretaceous, the abrupt increase in thickness of the Alam El Bueib (AEB) Formation towards the basin bounding faults (E-ENE) reveals the rifting influence, while during the deposition of the Alamein Dolomite Formation, the tectonic subsidence was probably limited with the smallest change in thickness (Bakr and Helmy 1990; Waly et al. 2001). The tectonic subsidence resumed with a slower rate compared to the AEB Formation thickness in the Late Cretaceous indicated by the smaller thickness of the Kharita Formation indicates that the tectonic subsidence
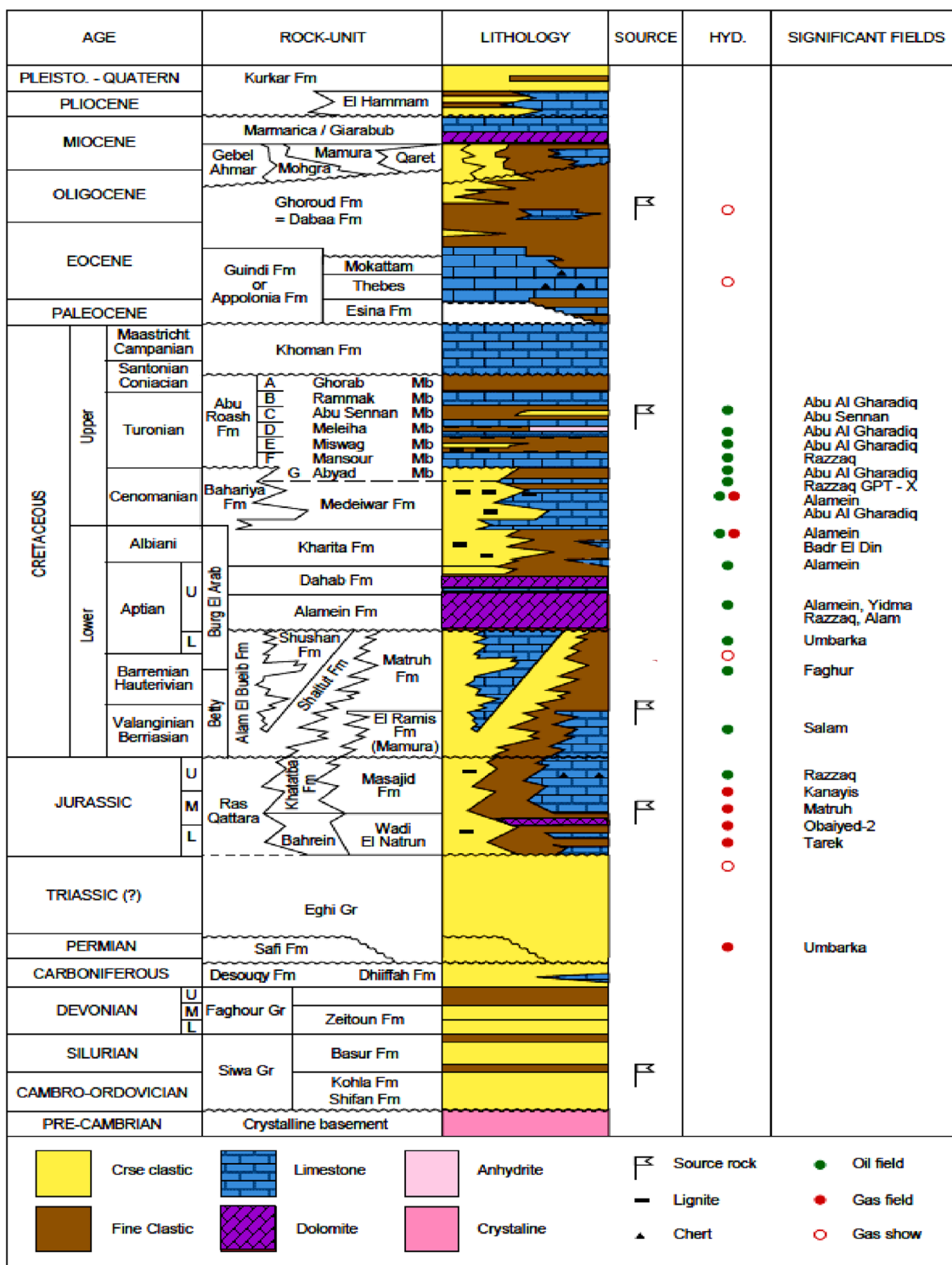
**Fig. 2** Stratigraphic sequence of the northern part of the Western Desert demonstrating the different formation ages and deposits content with oil and gas producing rocks. (Modified after Schlumberger, 1994, from Abu El Naga, 1983)

during Jurassic-Early Cretaceous rifting was episodic and the pre-rift stage had occurred in the Pre-Jurassic age (Moustafa et al. 1998; Barakat et al. 2019; Elsheikh et al. 2021).

According to Moustafa (2008), the NE-SW-trending Syrian Arc Fold Belt extended from NE Syria to the Western Desert of Egypt. This belt comprises several sub-parallel chains of NE-SW-trending elongated asymmetric antiforms
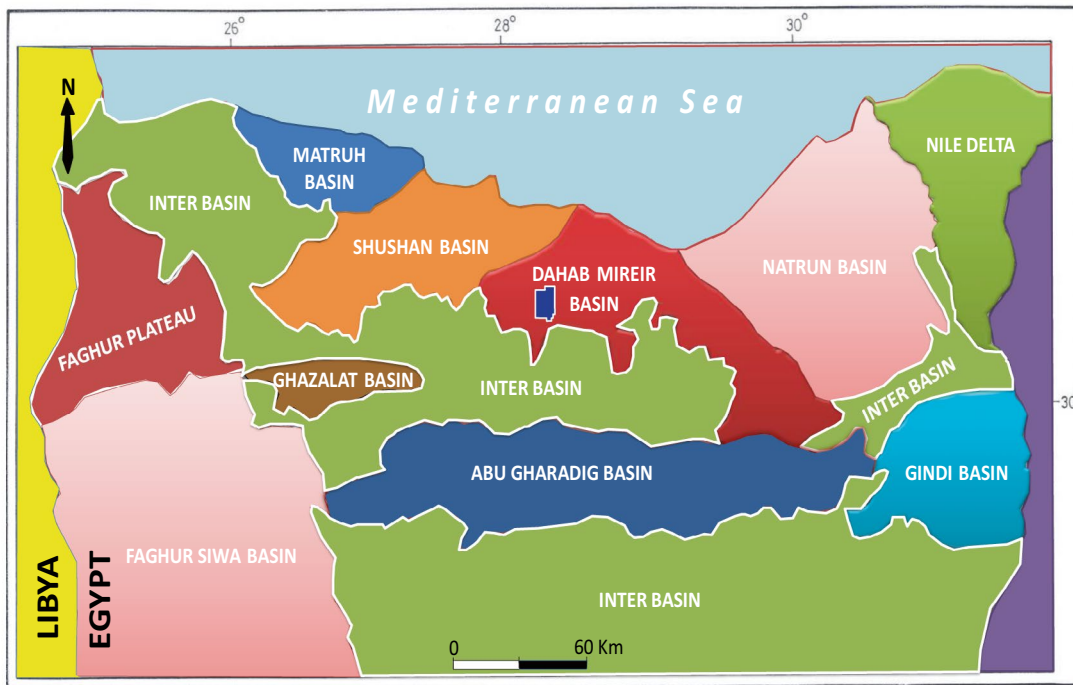
**Fig. 3** The Western Desert basins map shows the location of the study area, in blue color, concerning the Dahab-Mireir Basin ( Modified from Abd El Halim 1992)
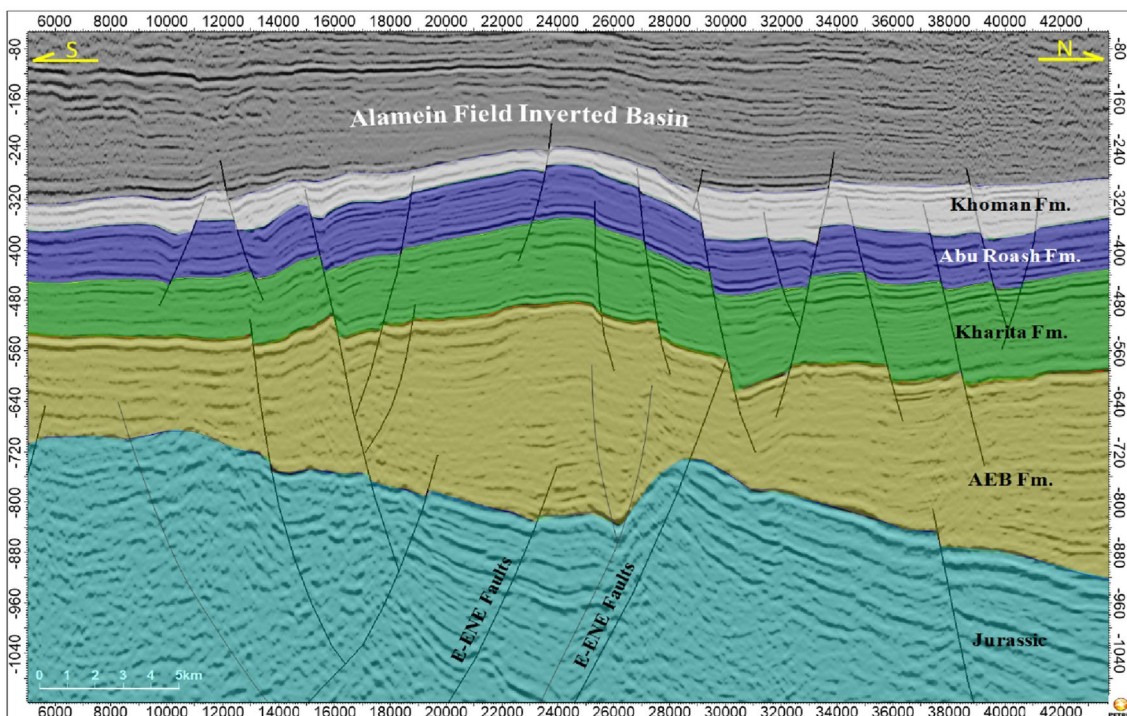


**Fig. 4** The structure identification of the Alamein field anticline showing the rifting system in the area and the basin inversion criteria consisting of the abrupt increase in thickness of the AEB Fm. against the basin bounding faults (E-ENE) of the Jurassic age and the obvious thinning of the Khoman Fm. of the late Cretaceous age over the crest of the culmination
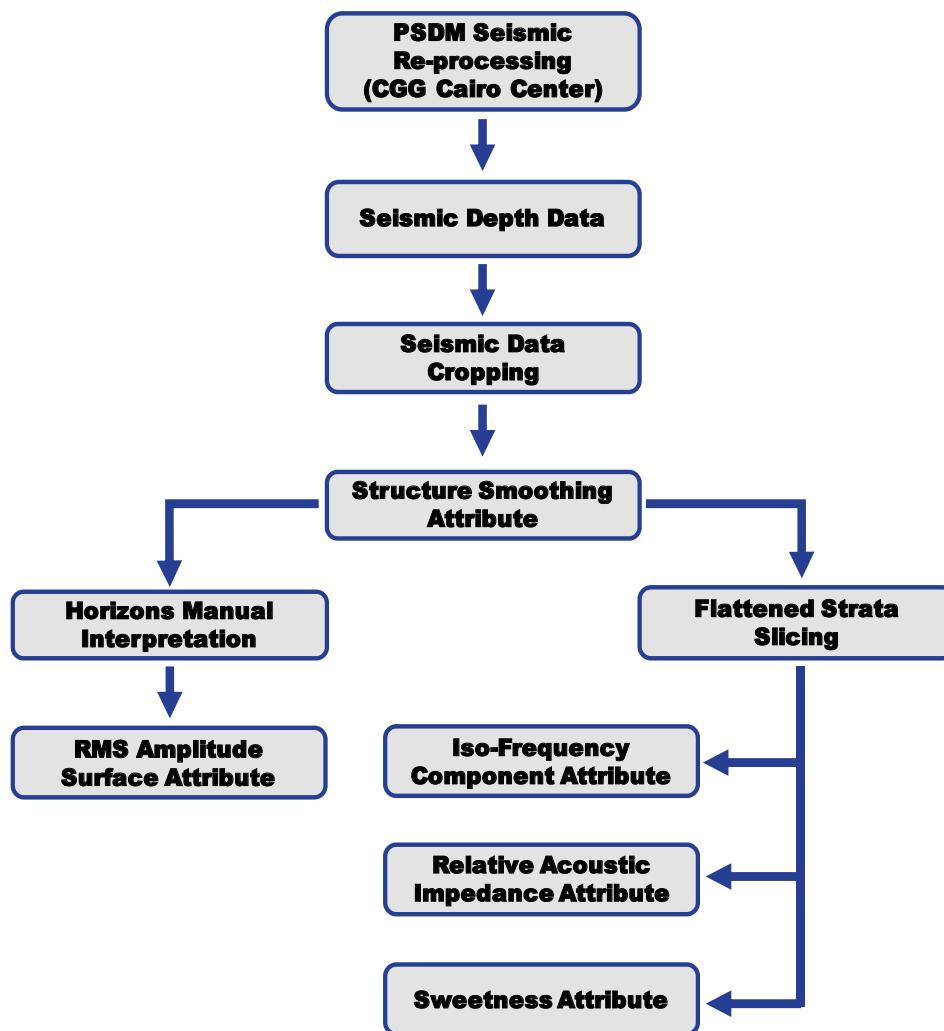
forming the Alamein and Yidma anticlinal fields and others. These antiformal features are cut by NW–SE extensional faults and have been interpreted as a typical consequence of basin inversion mechanisms (Ayyad and Darwish 1996).

The uplift of the formations caused by the Atlas and the Laramide Orogenies produced the Syrian Arc System forming the Alamein field anticlinal structure as one of the Alamein-Qattara Structural Ridges (Fig. 4). The field was defined by seismic interpretation as a local closure on a large NE plunging anticlinal regional element dissected by NW–SE major trending faults of the Cretaceous age (Bakr and Helmy 1990; ElShaarawy et al. 1992).
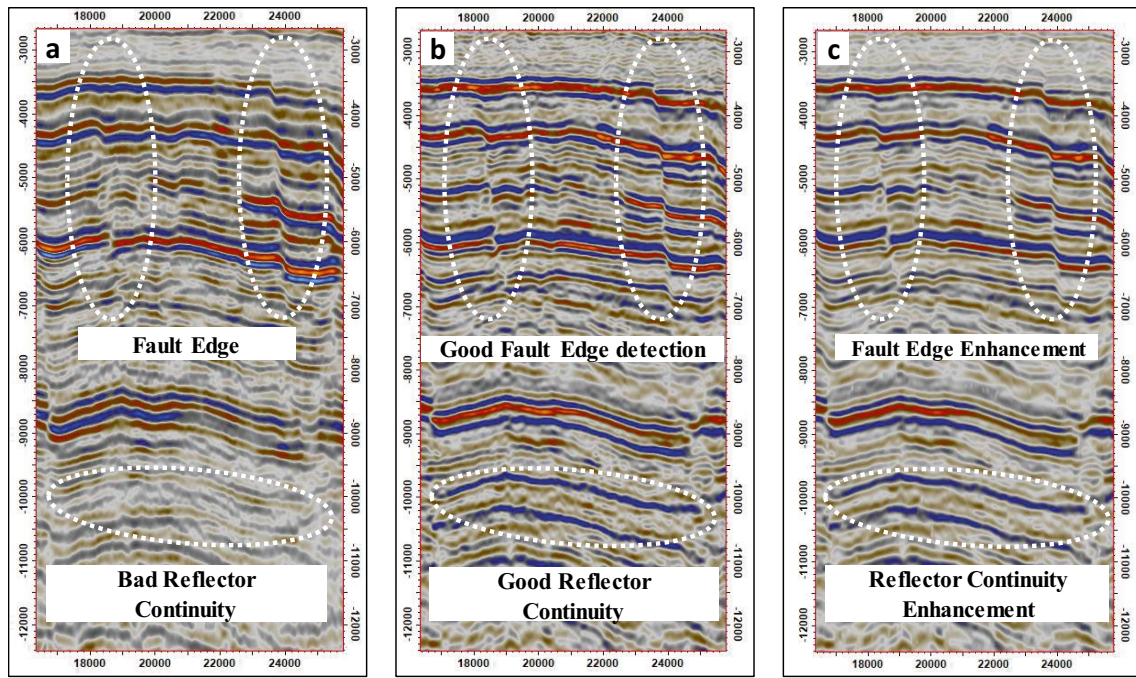
## Materials and methods

A detailed workflow was designed to demonstrate the applied procedures on the input data to achieve the main objectives of the driving workflow (Fig. 5). The first set of the input data used in this study was 3D seismic re-processed data for structure and stratigraphic interpretation purposes.

Seismic data processing underwent a robust workflow to enhance the signal-to-noise ratio, to obtain a perceptible improvement of resolution and the reflectors continuity in the area of study. This improvement made the manual interpretation of the targeted horizons easier for mapping the subsurface structural and stratigraphic elements, also; the data had been optimized and normalized for the subsequent attributes analyses. The second set of data was the well data, which was used to define the petrophysical parameters of the Aptian sand reservoir pay interval and integrate the resulting data from the data analyses with the interpreted seismic data to drive the conclusions. The third dataset was the production data for summarizing and tabulating the production history of the Aptian sand producing reservoir and collecting real information and analogies from the producing wells to explore the unknown areas of the interesting reservoir nearby the producing Alamein field. Seismic interpretation was achieved on Petrel™ (version 2017) of Schlumberger Inc.

The seismic interpretation was used for identifying the geological setting of the study area for oil exploration by

**Fig. 5** A detailed workflow chart demonstrating the applied procedures for the horizon manual interpretation and the attribute analyses for delineating the stratigraphic features in the structural affected study area

**Fig. 6** Structural smoothing attribute applied for the seismic data (**a**) Old seismic data (**b**) Re-processed data and (**c**) Edge-enhanced Gaussian smoothing. The effect of the applied attribute appeared in the enhancement of edge detection of faults and the continuity of the interested reflectors even more on the reprocessed data which improved picking stability
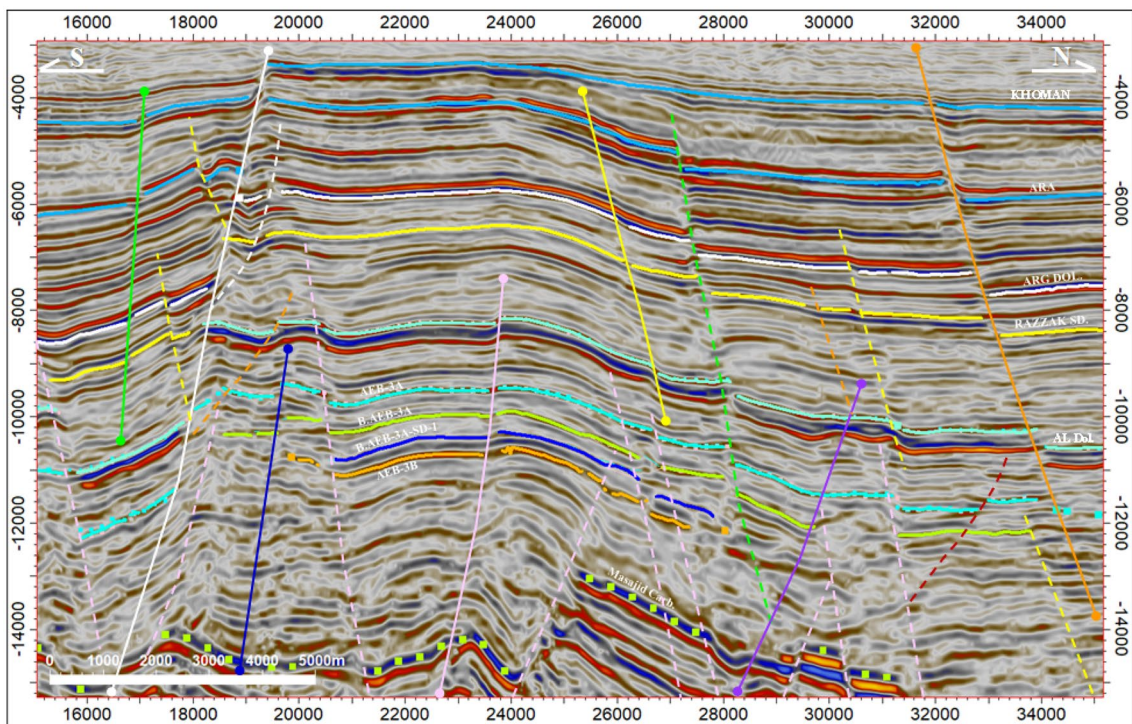


**Fig. 7** The manual seismic interpretation on the structural smoothed seismic volume shows the fine detection for the fault edges which helped in the interpretation of the fault framework and the enhanced continuity of the reflectors that aid in the interpretation of the interesting horizons which used as a guided image to resolve the subsurface structure and stratigraphic geological complexity
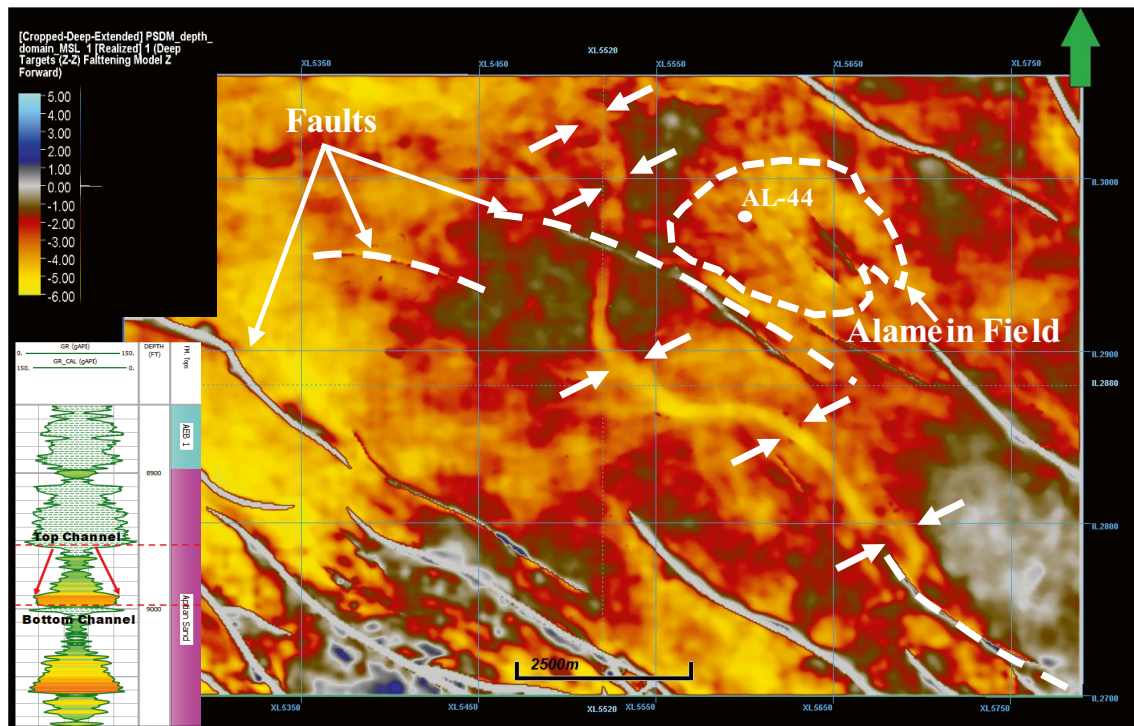
**Fig. 8** Depth slice at −8000 ft on the flattened seismic volume viewing the reflected geological feature on the top of the producing Aptian sand reservoir in the Alamein field expressing a meander channel system
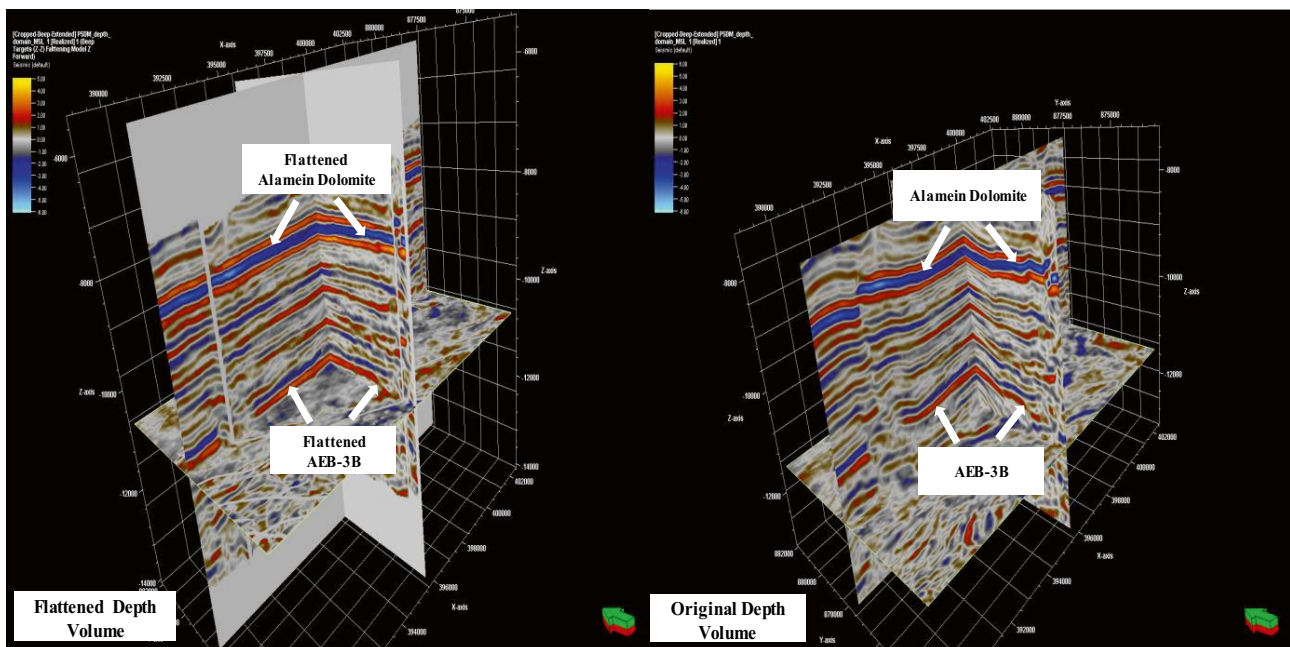


**Fig. 9** 3D View displays the flattened depth strata on the flattened seismic volume using the flattened stratal slicing method on the interpreted Alamein dolomite and AEB-3B horizons, the method provided an obvious increase in horizontal resolution for depositional history description

mapping the subsurface seismic data and determining the best well location (Abdullah et al. 2021; Barakat et al. 2022). Then the seismic attributes analyses were used as an effective tool for measuring and analyzing the seismic anomalies that occurred due to changes of the seismic waveform at the geologic interfaces; these changes reflect the behavior of the subsurface rock properties and play a key role in the seismic reservoir characterization to determine the location of hydrocarbon accumulations. The attributes analyses provide one approach in measuring and analyzing these modified waveforms (Taner et al. 1994). These analyses are quantitatively not as reliable as the developing methods of seismic elastic rock property analysis; however, they are strong indicators of formation variability and powerful interpretation tools to dissect the seismic traces into their constituent components, amplitude, phase, travel time, and position (Schlumberger 2008). A useful seismic attribute either is directly sensitive to a certain geological anomaly or rock property and allows defining the structural or depositional environment. For instance, bright spots (high reflectivity) have indicative attributes directly related to the amplitude energy of seismic wave reflectivity which is sensitive to hydrocarbon pore fluid (Chopra and Marfurt 2005).

Sequentially, the methodology started by cropping the seismic depth volume for the interesting study area, and then the structure smoothing attribute was applied for the cropped volume (Fig. 6) which improved picking stability,

highly defined faults edge, and reduced noise without degrading the original data (Randen et al. 2000; Fehrmers and Hocker 2003; Barakat and Dominik 2010). Subsequently, the structurally smoothed seismic volume was used for manual interpretation of the horizons of interest, and depth maps were constructed to identify the structural style of the study area. Two horizons, Alamein Dolomite and AEB-3B, were then used as inputs to create a velocity model for the seismic volume. The flattened stratal slicing method increases the lateral resolution and defines the depositional history easily on the recovered geological surfaces by exposing the stratigraphic framework and settling the structure effects (Zeng et al. 1998).

The flattened seismic volume was used as input for a series of attribute analyses. First, the iso-frequency component attribute of different correlation frequencies was applied in addition, to relative acoustic impedance (RAI) and sweetness attributes. The iso-frequency component attribute is a patented seismic decomposition method that generates an attribute volume at user-defined frequencies to decompose the seismic data to their frequency components where the decomposition is performed locally and based on a short time window Fourier and continuous wavelet transformation (Pepper and van Bemmel 2001; Castagna et al. 2003). This creates an auto-correlation function that eliminates the phase information within the data, thus aligning the seismic energy at a defined position
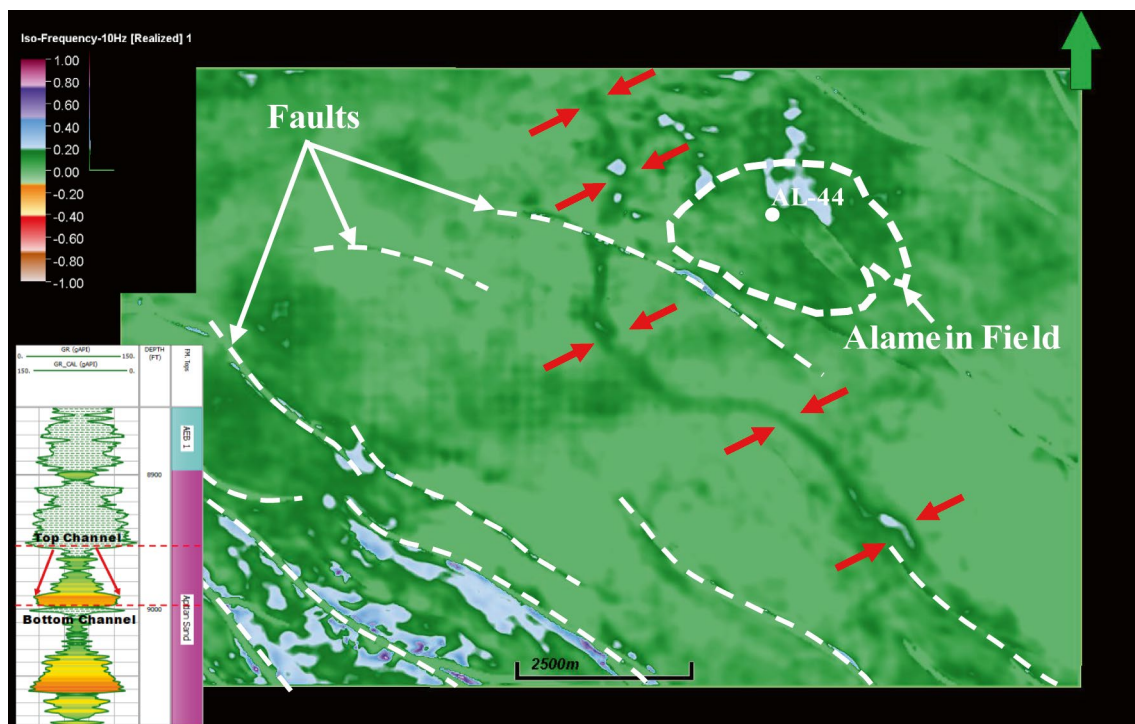


**Fig. 10** Depth slice at −8000 ft on the Iso-frequency component −10 Hz volume display the Aptian sand meander channel of 10 km in length and thickness reaches around 30 m
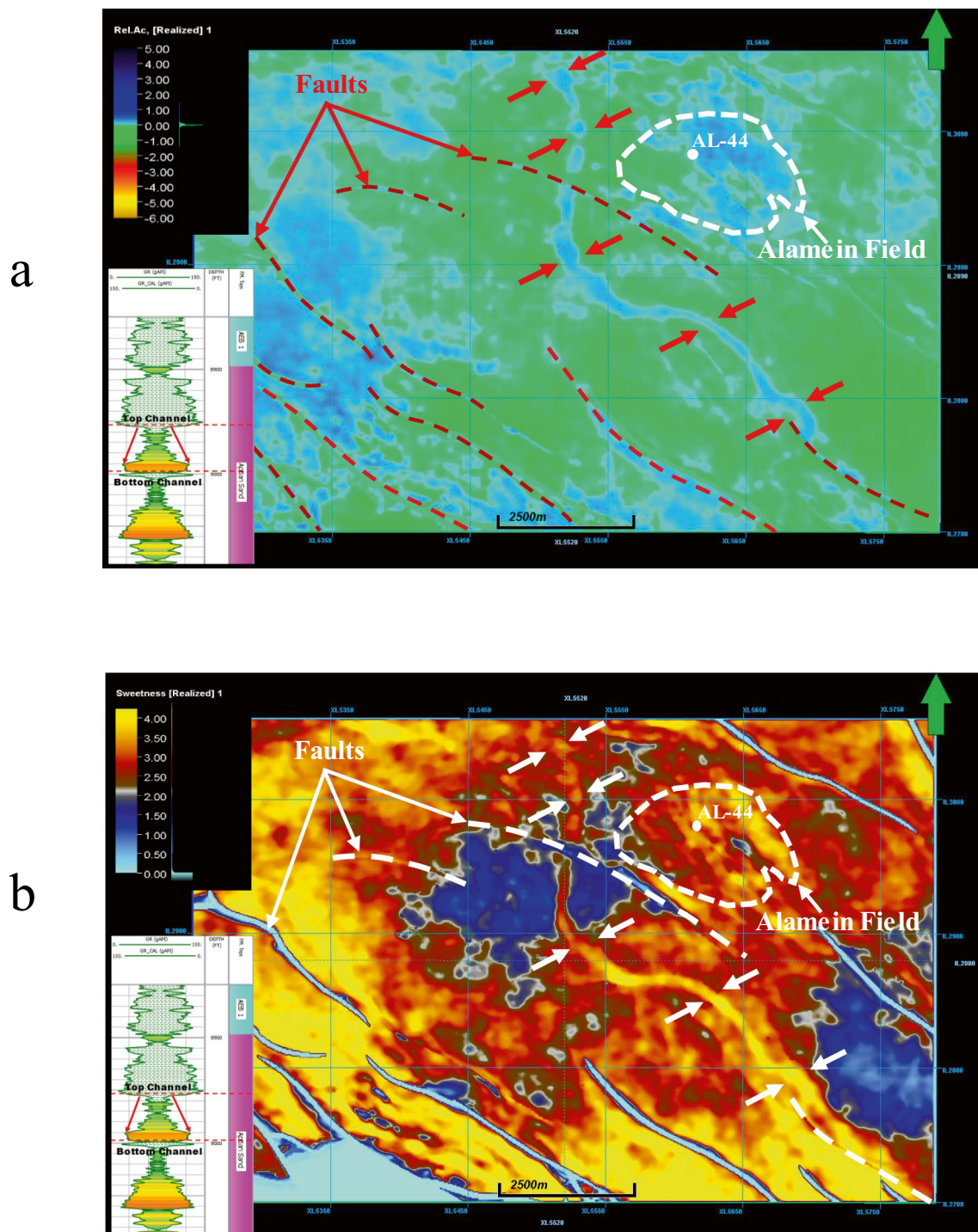
**Fig. 11** Depth slice at −8000 ft (**a**) RAI attribute volume and (**b**) Sweetness attribute volume viewing the Aptian sand meander channel as they are effective attributes in revealing the stratigraphic layers and sand bodies of development channel in shale

(zero lag). This attribute is routinely used for thickness prediction (Partyka et al. 1999), seismic geomorphology (Marfurt and Kirlin 2001), and direct hydrocarbon detection (Sinha et al. 2005).

The relative acoustic impedance attribute according to Taner (1992) can be obtained by integrating the real part of the seismic trace assuming that the data are zero phase and broad bandwidth. Thus, the RAI data can be correlated with the well-log data and therefore be of more stratigraphic
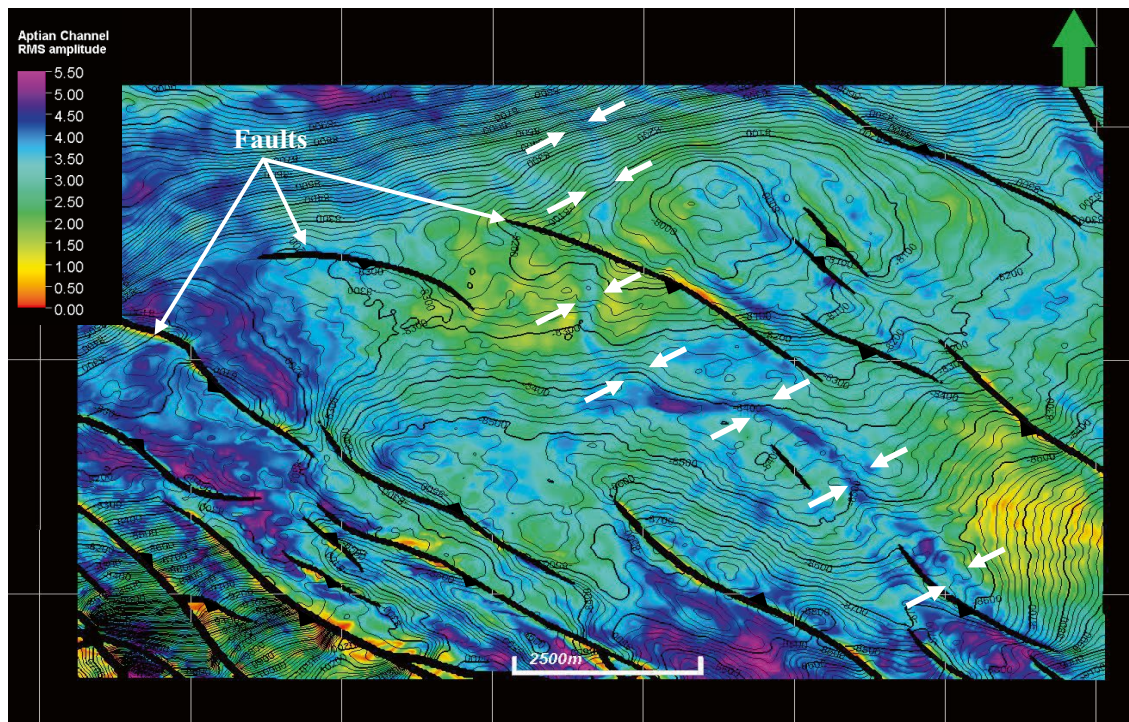
**Fig. 12** The RMS amplitude surface attribute reflection on the structure depth contour map of the Aptian sand interpreted horizon reflects the structural position of the detected channel

value for detecting a channel system. The sweetness attribute is calculated from the envelope (reflection strength) divided by the square root of the instantaneous frequency making it an effective attribute for delineating subtle discontinuities (Schlumberger 2008).

## Results and discussion

The manual interpretation of the fault framework and the subsurface mapping of the targeted horizons resolved the subsurface structure and stratigraphic geological complexities (Fig. 7). Because of the re-processing workflow applied by the CGG processing company, Cairo center accomplished the main objective on the seismic data by enhancing the reflector continuity of the interesting depths and fault edges. Furthermore, the structure smooth attribute applied to the re-processed data assisted the manual interpretation because it improved fault edges and increased continuity of reflectors.

The flattening of the depth volume led to detecting a meander geological feature on the top of the Aptian sand reservoir nearby the producing Alamein field, which was hard to be distinguished by the ordinary seismic interpretation methods (Fig. 8). This meander channel is discovered for the first time in the study area. The definition of the depositional history for the area was essential to understand the stratigraphic accumulation. Subsequently, proportional

depth slices were produced representing stratal surfaces inside the flattened depth volume using the flattened stratal slicing method (Fig. 9).

Consequently, stratigraphic attribute analyses started by using the flattened volume as an input for the different components of iso-frequency attribute analysis (5, 10, 15, and 20 HZ), which led to decompose the seismic data to their acquired frequency components and achieved the target from the analysis by delineating the geometry of the distinctive meander channel of the Aptian sand. The channel extended about 10 km in length with a width of about 160 m in the narrow part, while it reaches about 350 m in the wider part of the channel and reaches a thickness of around 30 m (Fig. 10).

However, another attribute analysis was acquired by the relative acoustic impedance (RAI) and sweetness attributes. The resulting attribute volumes positively confirmed the presence of the channel feature as the RAI attributes used for revealing the stratigraphic layering and unconformity surfaces, while the sweetness attribute is effective in developing the channel system when it appears as sand bodies in shale (Fig. 11).

After detecting the channel geometry on the flattened and different attributes analyses volumes, it was necessary to identify the structural setting of the channel, on the original depth volume, to determine the drilling location for testing the productivity of the channel. The RMS amplitude
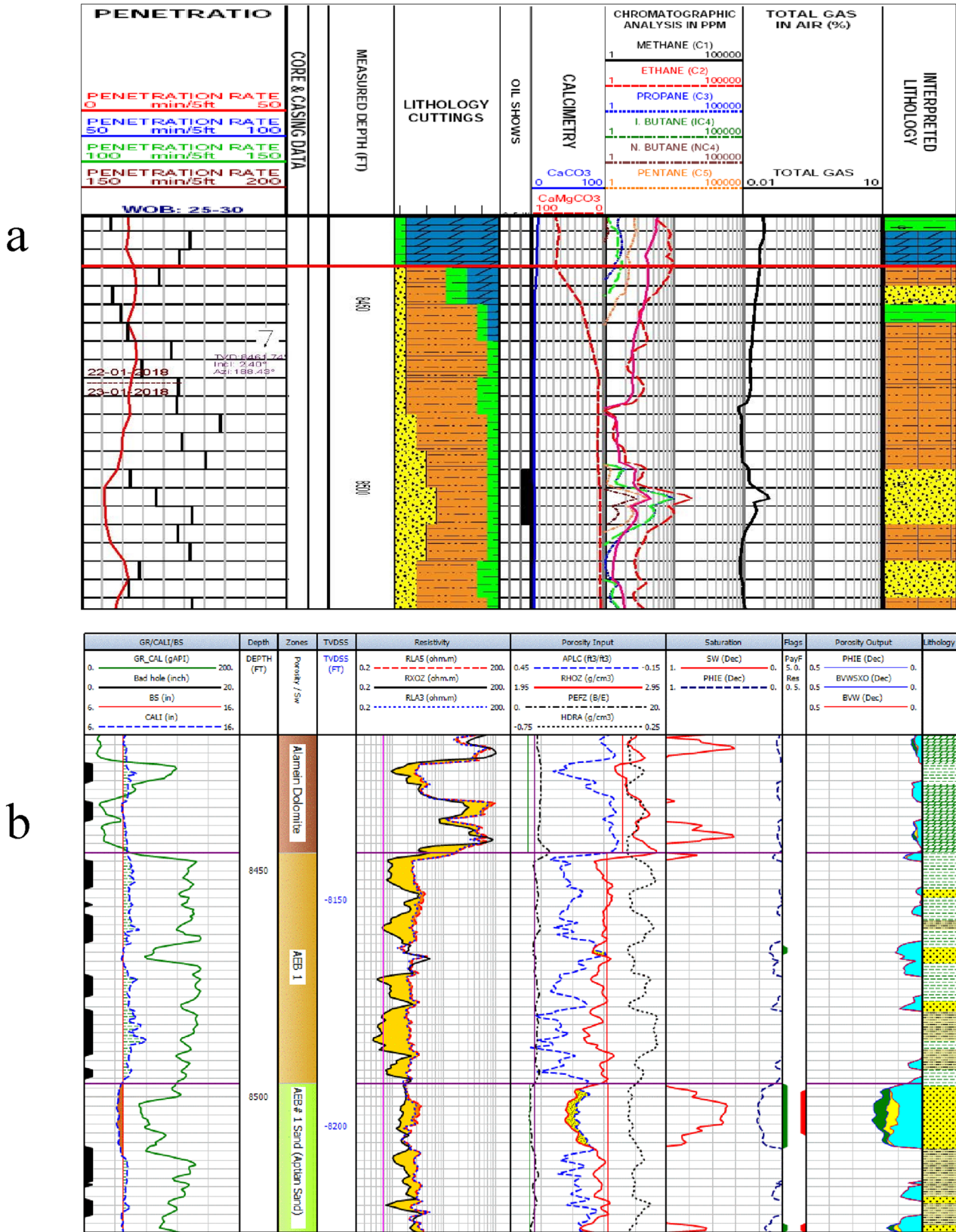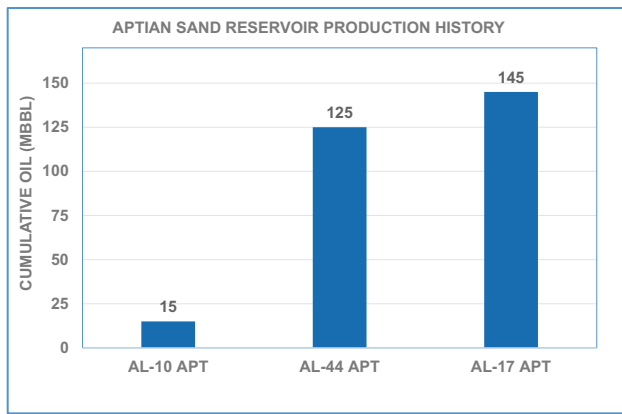
**Fig. 13** The Aptian sand reservoir quality in the producing Al-44 well (**a**) Mud log displays the recorded good oil and gas shows and (**b**) The petrophysical evaluation for the electrical log data displays the reservoir petrophysical properties

**Fig. 14** The cumulative production of the Aptian sand reservoir in the produced wells of the Alamein field. The reservoir produced from well Al-10 and AL-17 and still producing from AL-44 102 BOPD

could reflect the hydrocarbon indication in the seismic data and can map the geological features. Accordingly, the RMS amplitude surface attribute was applied guided by the interpreted Aptian sand depth surface and specific character on seismic data. The print of the channel was successfully noticed on the top of the horizon, and the attribute of the RMS amplitude was reflected on the depth map to define the structure depth of the extended channel (Fig. 12).

The productivity of the Aptian sand reservoir was well recognized and the petrophysical evaluation for the producing wells in the Alamein field reflected the reservoir's good quality. The petrophysical evaluation depended on the recorded electrical logs to estimate the important reservoir properties such as porosity, water saturation, and pay zone intervals. The conducted evaluation for the reservoir interval recorded the properties of 19% average effective porosity, 61% water saturation (Sw), and a net pay interval of 12 ft. Also, the good oil and gas shows were recorded on the mud log (Fig. 13). The production history verified the productivity of the reservoir from 1996 until now and the cumulative production recorded in the reports reached 285 MBBLS oil of 22° API and it still produces about 102 BOPD with 26% water cut from one well Al-44 (Fig. 14).

Although all the interpretation and analyses proved the presence of the meander channel system of the Aptian sand reservoir in the Alamein area, it is important to mention that all the results could not prove the hydrocarbon productivity of the detected channel system because there is no drilled well penetrated the channel's body. This was the hardest limitation to explore the channel production behavior but depending on the analogy from the cumulative production of the adjacent Alamein field wells from the reservoir, it will prompt to intensify the efforts to test the productivity of the detected channel to increase the production from this motivating reservoir.

# Conclusions

The re-processing of the old acquired 3D seismic data enhanced the reflector continuity and fault edge definition, and this facilitates the manual and automatic interpretation of the targeted reservoir.

Structure smoothing attribute improved the picking stability and aided in identifying the subsurface structures for applying the attribute analyses efficiently. The flattened stratal slicing method provided an increase in horizontal resolution, and as a result, it reflected the stratigraphic feature of the Aptian sand channel in the Alamein area.

The iso-frequency components, RAI, and sweetness attributes attested to be very effective in delineating the geometry of the significant Aptian sand channel of about 10 km in length with a width of about 160 m in the narrow part, while it reaches about 350 m in the wider part of the meandering channel and a thickness reaching around 30 m. The RMS amplitude surface attribute was applied to the interpreted depth surface of the Aptian sand reservoir to map the structure depth of the channel extension.

The petrophysical evaluation and production history of the Aptian sand reservoir declared the power of the reservoir productivity. It produced about 285 MBBLS cumulative oil since 1996 and is still producing 102 BOPD with 26% water cut (WC) from one well (Al-44).

Although the Aptian sand reservoir is produced from three wells in the Alamein field no well has penetrated the detected channel in the Alamein area accordingly, this will prompt to intensify the efforts to test the productivity of the detected channel to increase the production from this motivating reservoir.

## Declarations

**Conflict of Interest** Not applicable.

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