RESEARCH PAPER

Delineation of an inversion structure of Upper Jurassic-Lower Cretaceous succession based on interpretation of seismic data of Alamein oil field, Northern Western Desert, Egypt

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Abstract

This study aims to evaluate an inversion structure and detailed structural elements based on a set of two-dimensional seismic lines at the Alamein oil field. A three dimensional structural model has been built, tied with drilled wells and picked horizons, to display the different structural elements controlling the main various horizons of the Alamein field. The belt movement caused a regional extensional regime during the Jurassic and early Cretaceous period then followed by a stress movement at the Late Cretaceous-Oligocene period that formed the Alamein inversion. Alamein oil field is characterized by a positive inversion structure caused by the Jurassic-early Cretaceous master inverted fault. This inverted fault is situated in the central part of Alamein field bounding a half-graben trough accompanied with gradual subsidence toward the southeastern part of the study area with a continued deposition of the lower Cretaceous sediments. Alamein field represents a nearly E-W asymmerical anticline overlying the late Jurassic-early Cretaceous and dissected by a large number of NW-SE faults which mainly died out in lower Cretaceous and rare of them passed to the deepest level (Jurassic period). At the beginning of the Jurassic time, many faults of ENE-WSW direction were detected which may be initiated from pre-Jurassic and extended to the younger levels due to the movement of belts.

Keywords: Three dimensional structural model, Alamein basin, Inversion structure, Seismic interpretation

1. Introduction

The inversion structure occurs when the basins or half-grabens with varying degrees are turned inside out by compressional forces that reverse the deformation along preexisting normal faults.[1] Harding[2] had classified the inversion into two types: the first one is positive inversion which described as the suffering of any area from subsidence to uplift, and the second one is negative inversion which refers to the area is suffering from change of uplift to subsidence.

The Alamein basin, situated in the northern Western Desert of Egypt, is considered one of the large sedimentary basins which host productive oil fields like Horus, Razzak, Yidma, and Alamein (Fig. 1A). It is located to the north of Abu Gharadig basin and the southeast of Matruh basin. Alamein basin's structural boundaries are delineated by the Dabaa platform to the north and the Qattara platform to the southwest.[3]

This study refers to the Alamein oil field and displays a detailed illustration of seismic data to identify inversion and footwall shortcut (FWSC) structures. Alamein oil field covers an area from 28° 36′ 00" to 28° 50' 00"E longitudes and from 30° 24' 00" to 30° 48' 00" N latitudes (Fig. 1B). The thick section of the Turonian and Cenomanian reservoirs is

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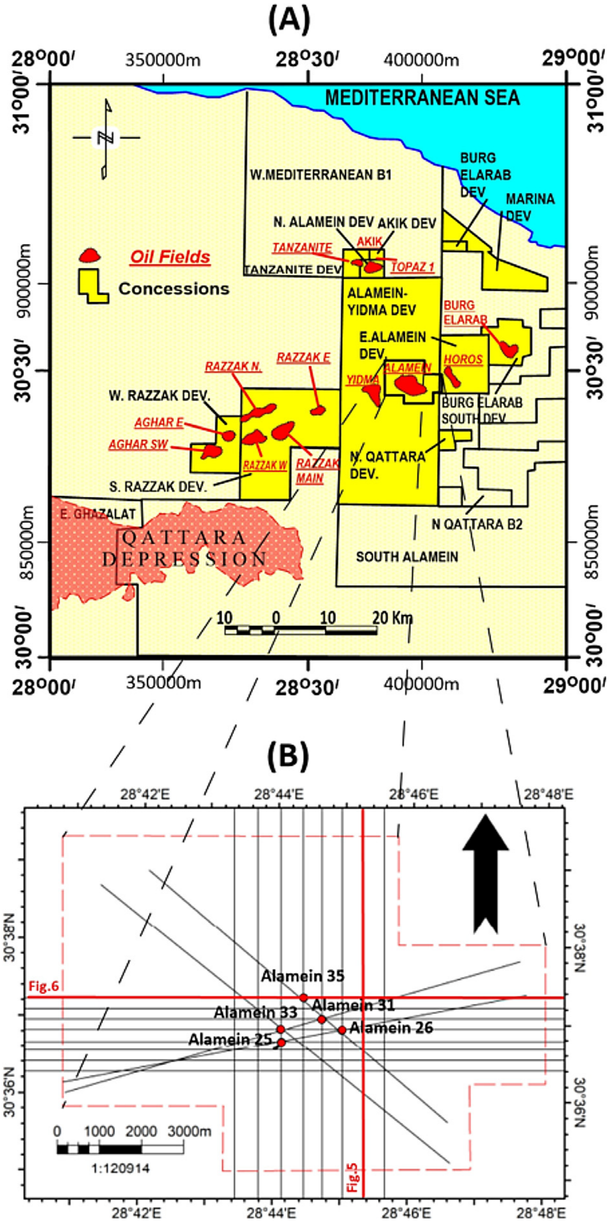

Fig. 1. Location map (A) Main concessions and oil fields of Alamein basin, (B) Seismic lines and drilled wells of Alamein oil field.

detected by interpretation of the two dimensional (2D) seismic sections where reservoirs are deeper and tracking of its geometry and boundary became more challenging.

This paper targets to evaluate a positive inversion structure in Alamein field which was caused as a result of compressional and tensional movements (mechanism of inversion). This paper is a trial to understand the relationship between the tectonic and inversion structures. By constructing a 3D structural model from picked horizons and wells data the study became easy, possible and clearer.

2. Geological setting

In the Western Desert of Egypt, petroleum investigations have been focused on its northern part. The occurrence of petroleum is closely attributed to the tectonics and stratigraphic history of the northern Western Desert which led to many reservoirs controlled by various structural traps. The litho-succession of the northern Western Desert (Fig. 2) is characterized by a thick sedimentary section from Paleozoic to Cenozoic deposits with an increasing thickness from south to north and northeast areas to become more than 9200 m.

The Arabo-Nubian Shield and the Tethyan Sea are the two main elements that controlled the sedimentation of the entire stratigraphic column over the northeastern corner of Africa.[4] The stratigraphic section consists mainly of alternating cycles of classics and carbonates as a result of several successive transgressions and regressions of the sea[3] so the sedimentary cover in the northern Western Desert is characterized by various environments of deposition[5–7] in addition to there are extensive variety of sediments.[8–10]

Tectonically, according to Said,[11] the northern Western Desert is part of the unstable shelf that has undergone five cycles of diastrophism throughout its history. These cycles include the following: (a) early Paleozoic, (b) late Paleozoic, (c) late or post Jurassic, (d) late Cretaceous-early Eocene phase when the northeast Syrian arcing system of folds was produced, lastly, (e) mid to late Tertiary resulting in deformations with tensional relief, as well as folding effects in the E-W and NE-SW trends.

The Western Desert contains a set of rift basins (Fig. 3). Numerous studies revealed that sedimentary basins in the northern Western Desert suffered from several phases of rifting during the Triassic to Barremian period.[12,13] According to Badalini et al.,[14] the predominant influence of large-scale plate tectonics served as the primary reason for regional subsidence, inversion, and consequently, the formation and evolution of basins, the distribution of sediment supply, and the formation of traps. Guiraud[15] considered a phase of rifting that initiated during the late Jurassic to early Cretaceous period, contemporaneous with the formation of the Mediterranean basins and the development of the southernmost Sirte rifts in Libya.

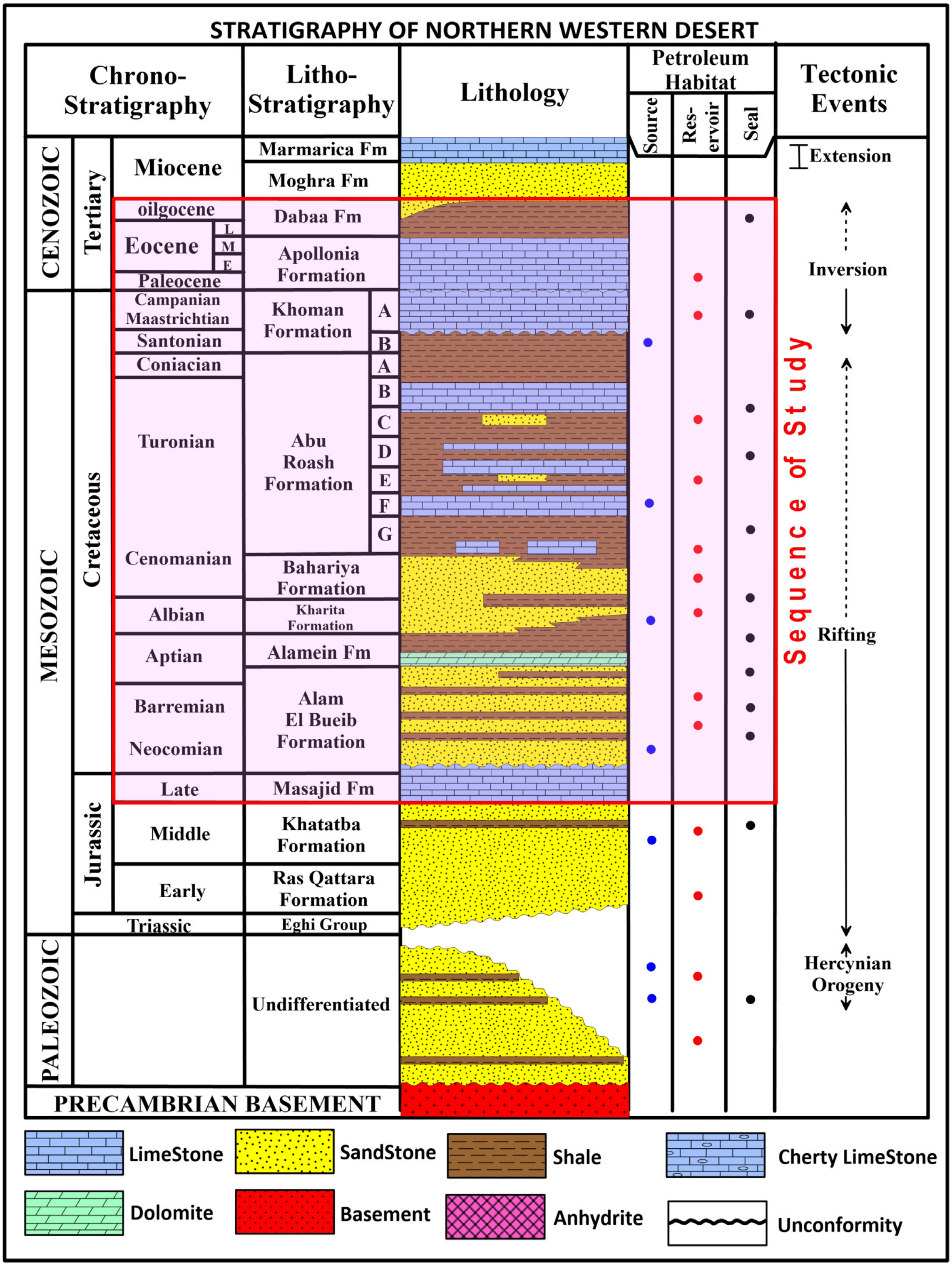

Fig. 2. Generalized litho-stratigraphic succession illustrating hydrocarbon distributions in the Northern Western Desert.[21]

Structurally, during the Jurassic and Early Cretaceous, the northern Western Desert exposed the regional extensional regime that created large faults which controls depositional thick sediments by forming half grabens. This thick section comprise reservoirs and source rocks which have been deposited in sub basins. The extensional phase extended to the mid Cretaceous where source rocks

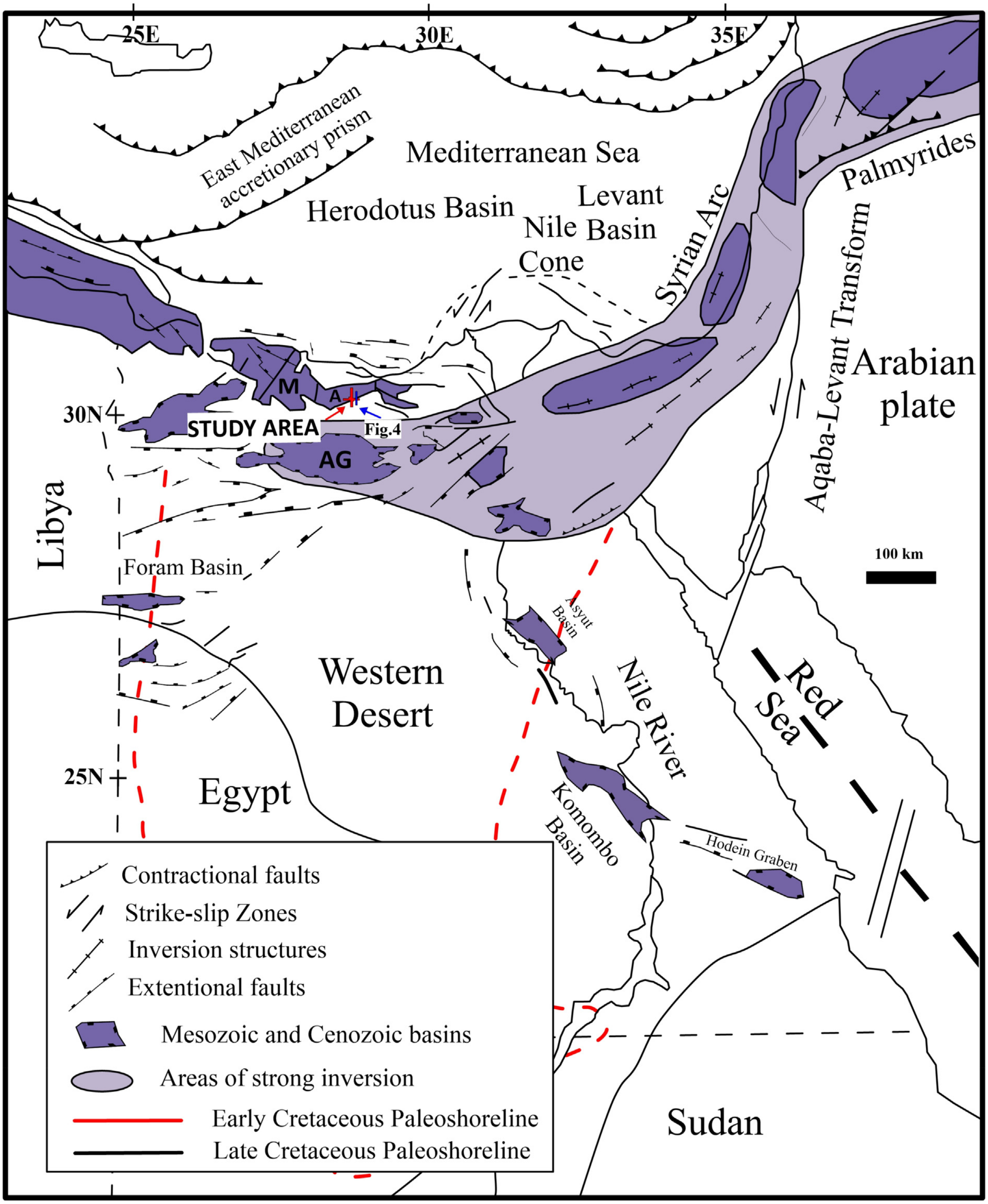

Fig. 3. Tectonic setting of northeast Africa and the eastern Mediterranean. This map is compiled from Guiraud et al., and Bosworth et al.[22,23] *A = Alamein basin; AG = Abu Gharadig; M = Matruh basin.*

became mature and oil beside gas was generated from previous source rocks which are found in the Turonian and Cenomanian reservoirs inside inverted basins. After that, extensional tectonic activity ended in the late Cretaceous by the beginning Syrian Arc inversion phase[16] that led to the inversion of deposited rift sub-basin into asymmetric antiforms.

3. Materials and methodology

The available data set in the Alamein oil field consists of five wells with a complete set of well logs and 20 2D migrated seismic time sections deuced from a 3D cube. The seismic sections are classified into eight lines directed N-S, eight lines oriented E-W direction, and four arbitrary lines in NW-SE and NE-SW direction.

Structure smoothing attribute is first step which applied to reduce the seismic noise, clearly delineate high reflectivity tops and ensure the faults cut-offs. The time-migrated seismic lines are tied to the available wells in the study area based on a check-shot of the borehole (Alamein-35). Seismic-to-well tie accurately detects reflectors that coincide with the tops of Cretaceous-Tertiary horizons. The selected tops from Dabaa to Alamein are picked along all seismic lines, after finishing the reflector identification and closing loops around five drilled wells.

According to Dolson et al.,[13] a discovery well named Zain-1X in the Yidma-Alamein development (Fig. 4) was drilled to a total depth of 17,000 ft (about 5200 m) and is the deepest well ever drilled in the Alamein basin and second deepest well in the Western Desert. By correlating the seismic section of the study area with that passing well Zain-1X, the top of Jurassic is detected in the Alamein oil field and is picked to define faults location and extension, and thereby to delineate the inversion structure.

Time to depth conversion process is carried out using velocity to form a set of depth structure maps. A 3D structure model is created from fault sticks and depth contour maps.

4. Results and discussion

4.1. Horizons and fault-picking

Figure 5A shows an uninterpreted seismic section oriented from south to north. Fig. 5B represents seismic section after applying the structure smoothing attribute to reduce the noise, enhancing picking formations and perfect detection of faults. The interpreted section (Fig. 5C) displays the geometry of seven formation tops and detects outlines of the various structural elements. The seismic line exhibits asymmetrical anticlinal horst, with dipping flanks towards the north and south. The anticlinal uplift has been dissected into several segments by a set of major and minor faults with diverse throws and tilts. It is noticed that the Oligocene to Cretaceous has the following features: (1) the absence of faults on top of the Dabaa formation, (2) the thickness of the Dabaa formation increase at southern parts, (3) the stress resulting from tectonic movements was active from Campanian-Maastrichtian time (Khoman formation) till Aptian age (Alamein formation) causing high anticline, which influences with aid of inversion structure in sediment transport routes, the deposition of reservoirs, and the formation of structural and stratigraphic hydrocarbon traps,[17] (4) the Cretaceous horizons are characterized with high thickness due to dome uplift in the

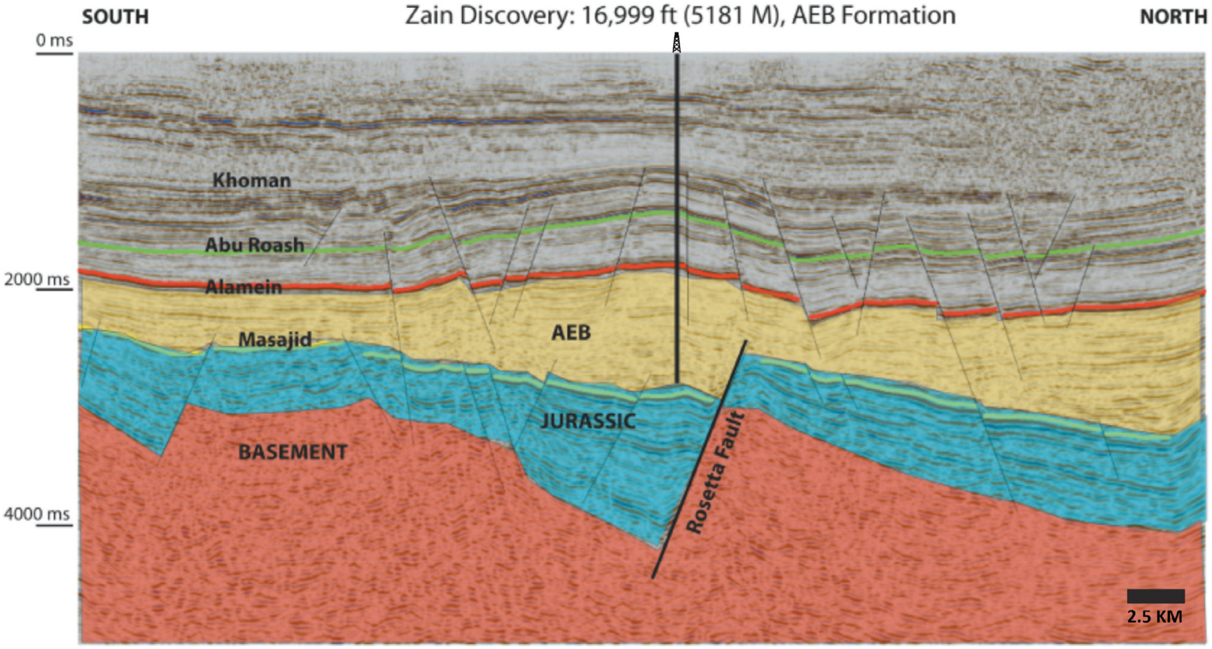

Fig. 4. South-north seismic section showing the Zain discovery well testing an AEB inversion structure above an undrilled Jurassic syn-rift.[15]

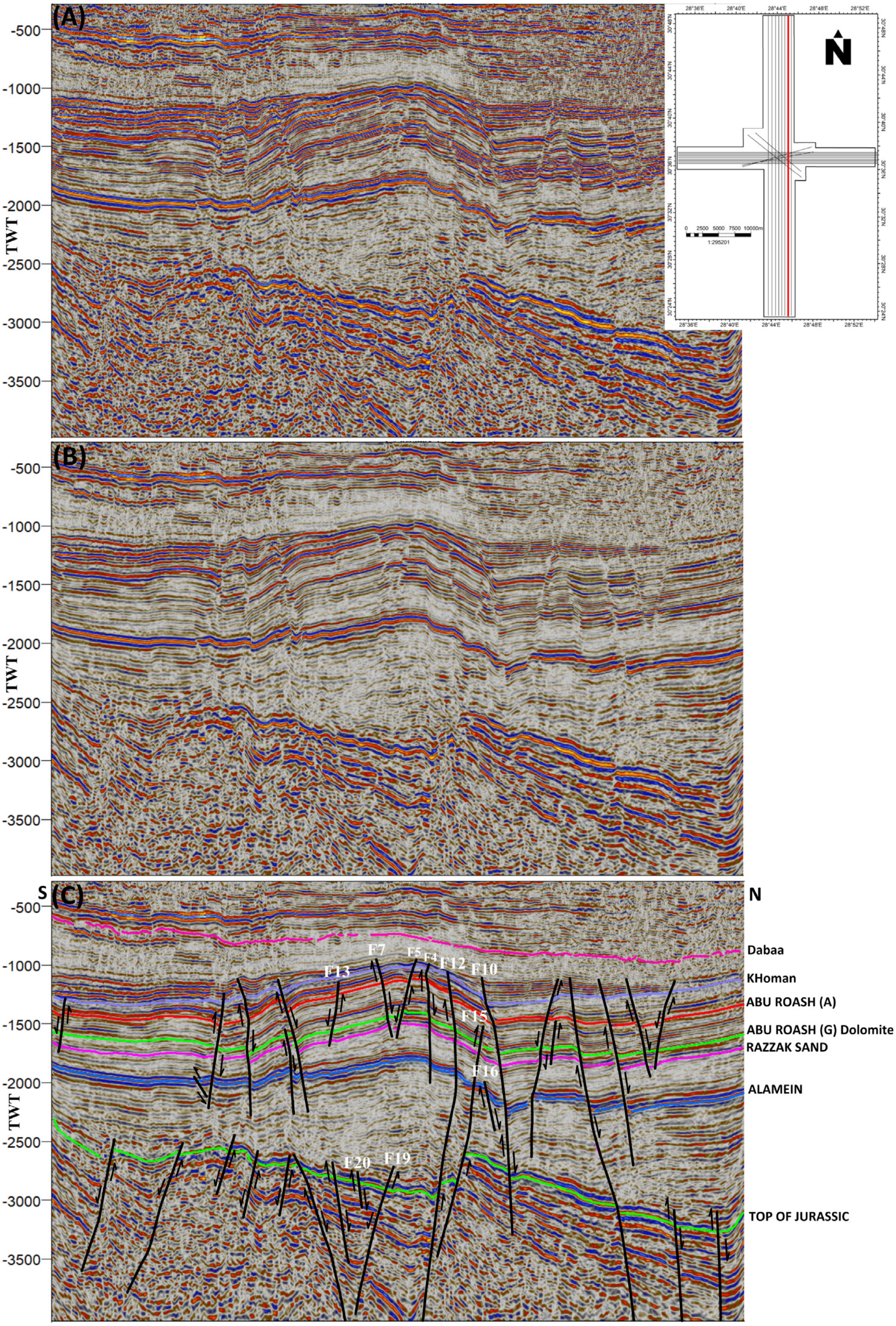

Fig. 5. ***(A)*** *Seismic section before applying structure smoothing attribute,* ***(B)*** *Seismic section after applying structure smoothing attribute and* ***(C)*** *Interpreted seismic section after applying structure smoothing.*

central part of the field and large vertical displacement of faults in the north, (5) the structure style is distinguished with a clear change in throw with depth, which may refer to that the area was subjected to many phases of subsidence, (6) extension of few major faults from pre-Cretaceous to late Cretaceous or some time above.

The top of the Jurassic is cut off with several faults from which a few major long faults extend and die out at the Cretaceous. Fault (F12) is defined as an inverted fault with high-angle segments which cannot be reactivated in the presence of sub-horizontal compressional stresses, even if there is a low coherence and friction pre-existing plane.[18,19] As a result, a new fault plane develops branching from inverted segments can be termed a foot wall shortcut fault (F15).[18] Extensional faults are characterized by segmentation, and sediments commonly enter the hanging-wall accommodation space where fault segments interact at transfer faults, accommodation zones, or relay ramps.[20] According to the invert extensional faults, awareness of extensional fault geometry and syn-rift sediment distribution becomes critical to knowledge the geometry of the resultant inversion. Fig. 5C also exhibits the Cretaceous anticline trap above inverted and FWSC faults which developed during the early Cretaceous inversion of Jurassic extensional faults.

Figure 6A exhibits another example of an uninterpreted seismic section extending W-E, tied with the Alamein-35 well while (Fig. 6B) shows a structurally smoothed seismic section. Fig. 6C shows the interpreted section with picking Oligocene Dabaa formation which appears uniformly geometry and had been deformed by major faults (F2, F3). Khoman formation is the top of the Cretaceous which disagrees with the overlying top by more manifestation of faults various in distribution, length, and displacement. Abu Roash (A) top shows approximately the same fault pattern and folding of the Khoman formation with a magnitude more than of Oligocene-Eocene time which indicates high compression activity during the period from Campanian to Coniacian. The Abu Roash (G) dolomite and Razzak Sand tops had been cut off through several faults formed en-echallan and graben shapes on the eastern side of the section. Alamein Formation is characterized by high acoustic impedance according to the presence of hard dolomite and dolomitic limestone. Alamein appears continuity of compressional force at Aptian time through the existence of folding. Faults of the Cretaceous age became lesser at the Alamein formation and did not extend to the Jurassic portion.

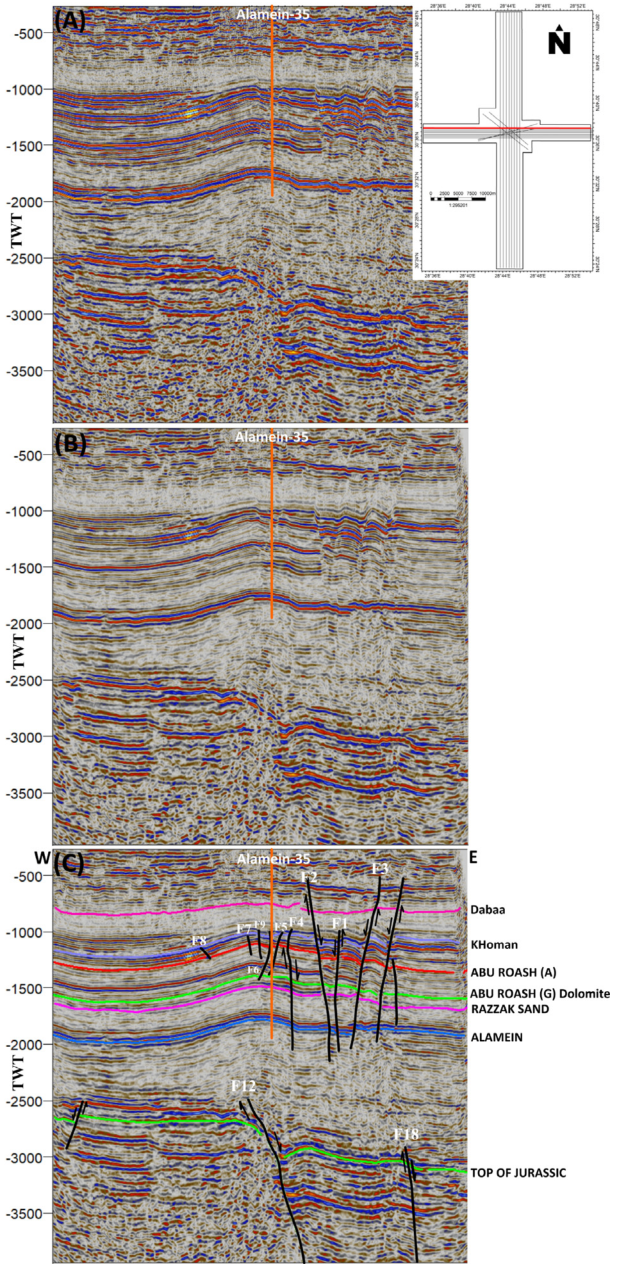

Fig. 6. (A) Seismic section before applying structure smoothing attribute, (B) Seismic section after applying structure smoothing attribute and (C) Interpreted seismic section after applying structure smoothing.

The top of the Jurassic is mainly composed of limestone belonging to the Masajid formation which is distinguished with good reflectivity relative to upper and lower layers. This Jurassic surface is dissected by a master inverter fault (F12) dipping to the east direction creating a large half-graben. It is noticed an increase in the thickness of Early-Cretaceous deposits above the hanging wall of this master fault. This master fault is followed by another fault (F18) that also dips to the east causing more subsidence for overlying sediments.

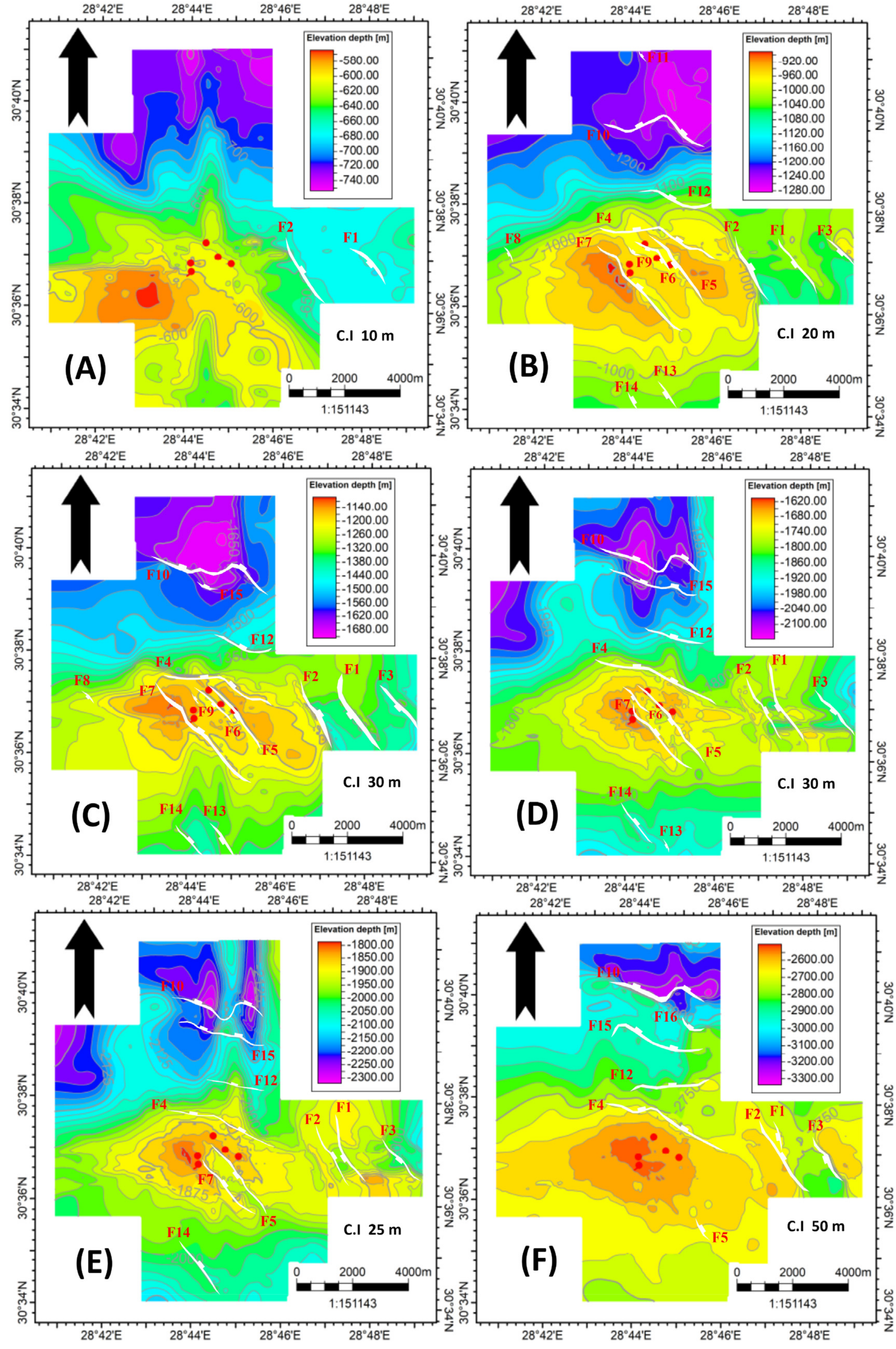

Fig. 7. Structure depth maps of tops A) Dabaa Formation, B) Khoman Formation, C) Abu Roash (A) Member, D) Abu Roash (G) Dolomite Member, E) Razzak Sand Member and (F) Alamein Formation.

4.2. Depth-structure maps

The structure time maps are converted to structure depth maps by interval velocity model to identify the geometry of each top. Seven structure depth maps are displayed on tops from Oligocene to Jurassic time. Fig. 7A shows the depth structure map of Dabaa formation which is characterized by the beginning appearance of an intersection between uplifted anticline in the southwestern portion and subsided area in the north. Some rejuvenated major faults (F1, F2) can be easily realized by forming a graben structure. It is characterized by the absence of minor faults. The top of Cretaceous is represented by the Khoman depth structure map (Fig. 7B) which reflects a higher level of deformation based on the presence large number of NW-SE major and minor faults cutting the high anticline into a set of segments. Abu Roash (A) depth structure map (Fig. 7C) displays an E-W-trending asymmetrical anticline in the central and southern area and was crossed by many NW faults. The (F10, F15, F12, and F4) faults are trending WNW-ESE direction and gradually forming subsidence toward the northern portion. Abu Roash (G) dolomite and Razzak Sand members depth structure maps show approximately the same structure style of Abu Roash (A) top with small differences in number, length, and throws of faults (Fig. 7D and E). The Alamein dolomite depth structure map (Fig. 7F) is characterized by a smaller number of faults compared with shallow formations. Fault (F10) is considered the boundary between the central uplifted area and northern subsided area sediments and can be represented as the border of the northern flank of the anticline. The central high is

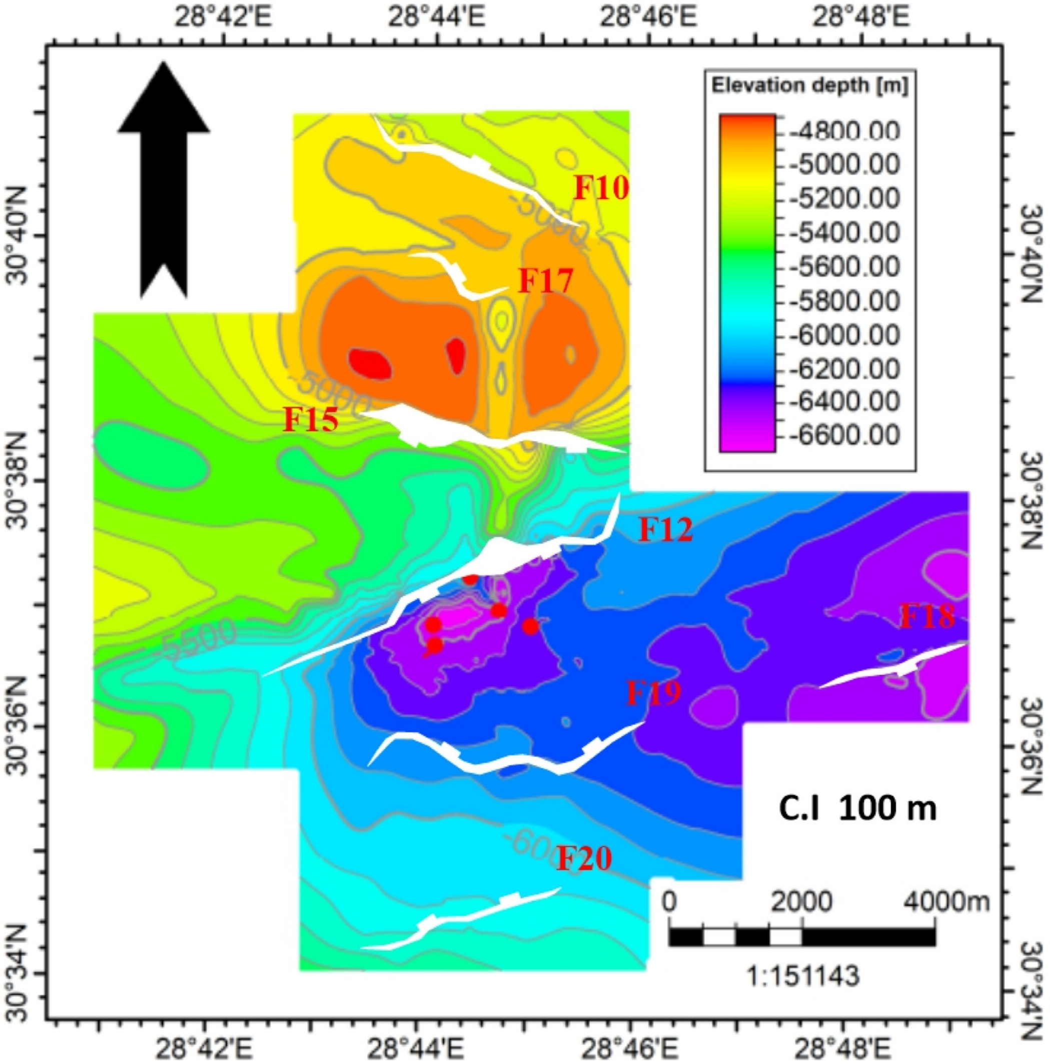

Fig. 8. Structure depth map of top Jurassic.

continuous in the lower Cretaceous which indicates persistence N-S compressive stress.

Figure 8 represents the depth structure contour map of the top Jurassic which is our case study of inversion. Jurassic depth map manifestate a reverse structure style relative to overlying Cretaceous layers. This top is crossed by a master NE-SW-trending inverted fault (F12) which may be initiated in the pre-Jurassic. This master fault is dipping to the southeast direction and creating a huge half-graben form. Presently, we may recognize the inversion that leads to presence high area in the north and a subsided zone in the southeastern separated by a master inverted fault (Alamein fault). The southeastern subsided area is coincide with the first occurrence of NE-trending normal faults belong to Syrian arc system. Jurassic rocks lying in the hanging wall of the inverted fault are cut with another extensional fault oriented from NE to SW.

Generally, depth structure maps of predicted top of Jurassic and Post-Jurassic rocks appear to change in length, shift in position, and mainly transition in throws of master inverted fault (F12) and FWSC fault (F15). The master fault (F12) shows a swinging from NNW-SSE direction in Cretaceous layers to an NE-SW trend on top of predicted Jurassic strata.

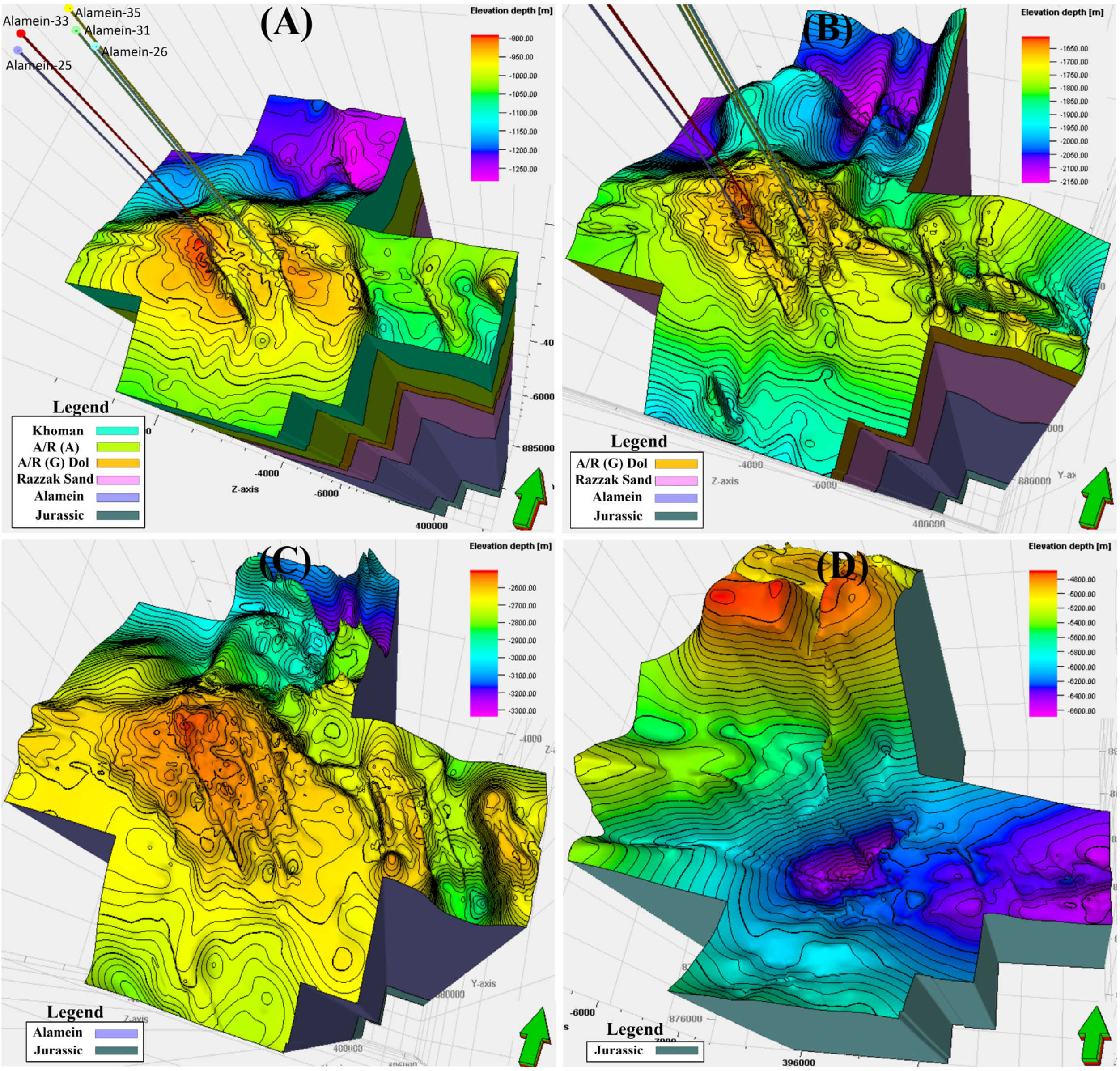

*Fig. 9. 3D Structural model of tops **A)** Khoman Formation, **B)** Abu Roash (G) dolomite Member, **C)** Alamein Formation and **D)** Top of Jurassic.*

4.3. Structural modelling

Based on the depth contour maps of picked horizons, a 3D structure model of Alamein oil field is built. Fig. 9A–C display the structure model in-depth domain tops of Khoman formation, Abu Roash (G) dolomite Member besides Alamein Formation which appears approximately the same

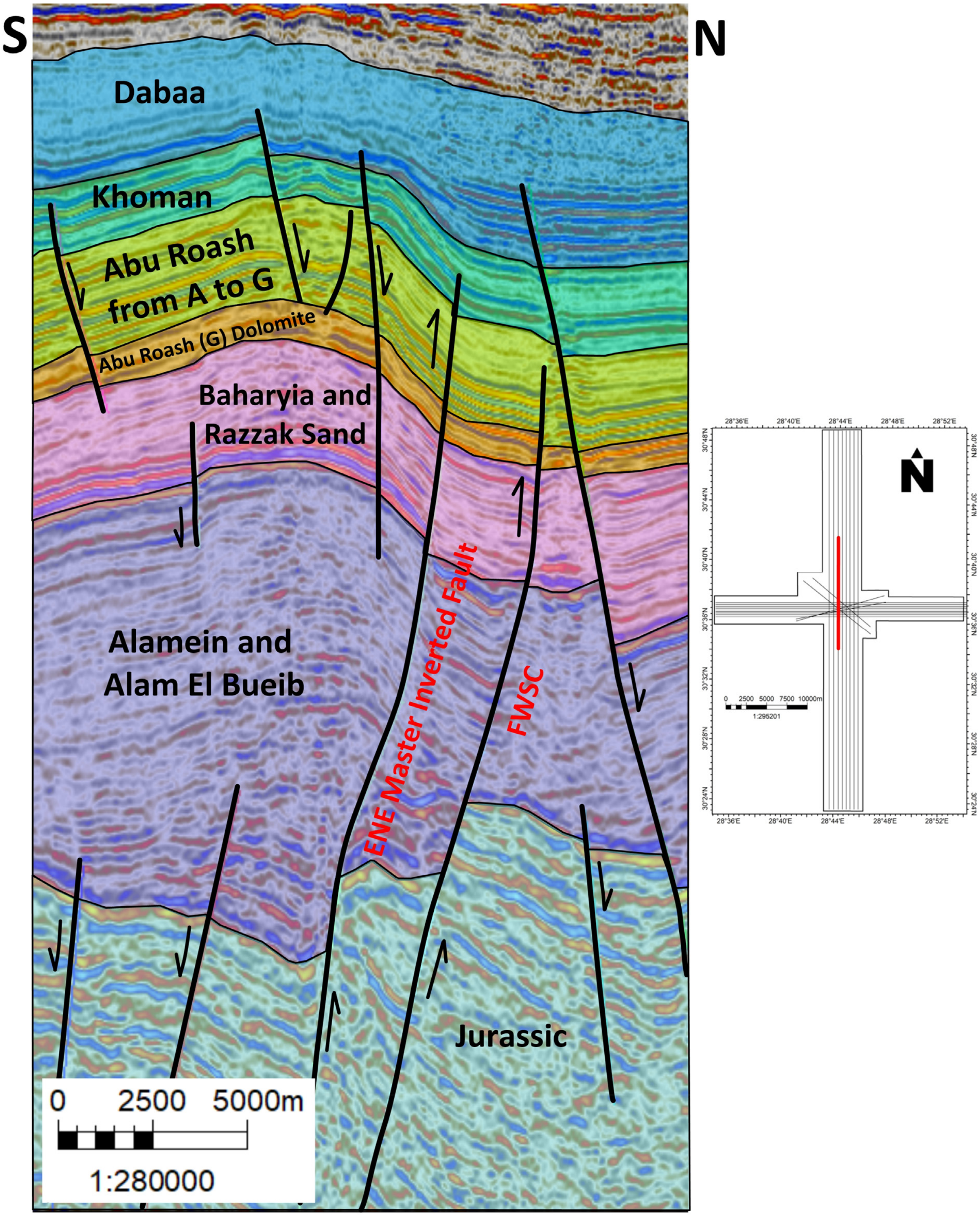

Fig. 10. Cross section resulted from 3D structure model oriented from south to north direction.

pattern distribution of various structural elements. They indicate that the study area in the Cretaceous period is characterized by a high uplifted anticlinal zone in the center of the area oriented nearly E-W direction. The area is affected by a series of NW-SE-trending normal faults differing in length and throw with the complete absence of NE-SW-trending faults (Syrian arc trend). Top of Jurassic (Fig. 9D) clarify the subsidence area in the center and the uplifted area in the north. The lack of the anticline refers to the absence of compressional force during the Jurassic period.

Figure 10 displays a cross-section extracted from the 3D model in time domain, in dip direction, and extends from south to north. The cross-section shows the Jurassic (Masajid) top that is controlled by ENE-WSW-trending master inverted and foot wall shortcut faults. The cross-section exhibits the Jurassic period affected by extensional force that forming a set of faults which are semi-parallel. Hanging-wall subsidence increased during the deposition of the early Cretaceous with first appearance of compressional force at the Alamein formation that created anticlinal form. The effect of compression continued and appeared clearly in Abu Roash zone while stress decrease gradually in the upper Cretaceous and Tertiary layers with generation of new faults and died out of extensional faults.

5. Conclusions

Alamein field is a part of the Alamein basin. It is affected by a main Jurassic-Early Cretaceous inverted fault. This main fault is oriented in the ENE-WSW direction and originated during the Jurassic period due to tensional forces, resulting in the formation of a half-graben. Half-graben produce hanging-wall accommodation space for depositing more sediments. The first appearance of the NE-SW-trending faults (Syrian arc trend) is dissecting the top of the Jurassic.

The Cretaceous period is characterized by E-W-trending inversion anticlinal form in the central area with subsidence in the north area. This anticlinal structure is cut by numerous NW-trending faults, including a few reactivated faults that extend from the Pre-Jurassic period, especially, master invert and FWSC faults. Cretaceous time is distinguished with absence of NE-trending faults.

The Oligocene age is represented by the Dabaa formation which reflect weak effect of Compressional force and the absence of minor faults with the presence of a few numbers of major faults compared with a Cretaceous period. Previous evidence refers to the Tertiary as a very stable period.

The seismic interpretation shows that the Alamein field is affected by two forces; the first one is the tension which forms half-graben besides initiating an invert fault in the Jurassic period and the second force is the stress force that is considered the main reason for the presence of anticlinal form, extension of inverted fault and generation of foot wall shortcut fault.

Ethics information

There are no conflicts of interest and this work not involving human or animal subjects.

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Author contribution

All authors were involved in conceiving and designing the idea, collecting data, processing the data, and writing the paper.

Conflicts of interest

There are no conflicts of interest.

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