Petroleum Res. J. Vol. 20 (2007); P. 59–76, 23 Figs.

Late Tertiary Subsidence and Tilting in the Sirt Basin and their Seismic Signatures

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ميل وهبوط حوض سرت خلال الحين الثلاثي المتأخر وبصماته السيزمية

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يقع حوض سرت في منتصف شمال ليبيا، ويعتبر من أكبر الأحواض إنتاجا للنفط في أفريقيا. وهو غير متماثل الشكل حيث يمتد بعرض 400كم في إتجاه الجنوب الغربي و120كم في اتجاه الشمال الشرقي نتيجة لعملية خفض منفردة تمت على نطاق واسع في فترة ما بعد عصر الأيوسين. ويمثل الموقع المحوري لغور إجدابيا العمق المحوري الحالي لحوض سرت حيث تكون كل الملامح التركيبية في الجزء الغربي للحوض (منخسف هون ومرتفع ودان وغور زلة ورصيف الظهرة – الحفرة وغور مراده ورصيف زلتن) وجزئه الشرقي (رصيف آمال ومنخفض مراغ ومرتفع الرّكب) مائلة وتتحرك تدريجيا إلى الأعمق في اتجاه محور غور إجدابيا.

تعتبر حركة هذا الخفض والميلان التي تمت خلال الحقبة المتأخرة من الحين الثلاثي من أهم الأحداث التكنوتية بحوض سرت. بدأت ذروة تولد النفط من الصخور الغضارية الرئيسية المولدة له بالحوض والتي تنتمي للعصر الطباشيري العلوي (الكامبيني-التيروني) إبان الأوليغوسين والمايوسين، عندما كان عمق صخور المصدر مدفونا تحت عمق 4000 متر. لذلك فقد حدث تولد وهجرة وتجمع النفط بعد هبوط كبير في فترة ما بعد عصر الأيوسين وفي وقت تشكلت فيه البنية والملامح الحالية للحوض.

يعتقد أن البصمات السيزمية مثل أنعكاسات حركات الكتل المرتبطة بإزاحة صدعية كبيرة في أفق المناطق المنخفضة (بعض من كتل ما قبل الكريتاسي العلوي تعلوها تكاوين غير سميكة من الكريتاسي العلوي) وحدوث صدوع عادية أو ذات ميل مضربي، نتيجة اختلاف ميل الكتل، ووجود قوة ضغط جانبية محلية على الأفق السطحي في آفاق غور المنطقة الضحلة (مولدة صورة بنيوية معقدة) وسمات خطية بنيوية تنتمي إلى الحين الثلاثي المتآخر، وذات اتجاه شمال غرب-جنوب شرق وشمال شرق-جنوب غرب، حدثت جميعها نتيجة هبوط وميلان رئيسيان أثناء الحين الثلاثي المتأخر.

Abstract: *Sirt Basin, situated in the north-central part of Libya, is the largest oil producer in Africa. Present asymmetrical configuration of the Sirt Basin with southwestern flank being about 400km wide and northeastern flank about 120km wide, is a result of a single, broad, large scale, post Eocene subsidence. The axial position of deep Ajdabiya Trough represents the present axis of the Sirt Basin. All the structural features in the western flank of the basin (Hun Graben, Waddan Uplift, Zallah Trough, Az Zahrah-Al Hufrah Platform, Maradah Trough, Zaltan Platform) and eastern Sirt Basin (Amal Platform, Maragh Low, Ar Rakb High) are tilted and have moved progressively deeper towards the axis of the Ajdabiya Trough.*

These major late Tertiary subsidence and tiltings are considered as one of the most important tectonic events of the Sirt Basin. The peak of the oil generation from the Upper Cretaceous Campanian-Turonian shales as the

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principal petroleum source rocks in the Sirt Basin was mainly during the Oligocene-Miocene time when the burial depth of these source rocks was below a depth of 4000m. Therefore, generation, migration, and accumulations occurred mainly after the huge post Eocene subsidence, at a time when the present structural configuration of the basin had already been established.

Seismic signatures such as reversal block movements associated with larger fault displacements in the shallower horizons (some deeper pre-Upper Cretaceous blocks have thinner overlying Upper Cretaceous formations); scissor faults and/or strike slip faults as a result of differential block tiltings; localized lateral compressional forces in the shallow horizons of the trough areas (generating complicated structural pictures); and NW-SE and NE-SW trending late Tertiary structural lineaments are thought to be mainly due to the late Tertiary major subsidence and tiltings.

INTRODUCTION

Structural evolution of the Sirt Basin shows that the gradual subsidence, associated with syndepositional fault movements, of the NW-SE trending platforms and troughs ended with a major subsidence associated with tiltings in late Tertiary time (Roohi, 1996a).

A very unique combination of thick sediments of up to 10,000 m with rich source rocks in the troughs versus much thinner sediments with prolific reservoir rocks on the platforms accounts for the productivity of the basin.

The main objective of this paper is to analyze the importance of this major late Tertiary tectonic event, and demonstrate that the present structural configuration of the Sirt Basin is the result of this movement. Structural complexities observed in seismic which are related to this subsidence and its associated tiltings are also discussed.

As the result of this post-Eocene tectonic event all the blocks in the western and eastern flanks of the Sirt Basin subsided rather abruptly. They progressively moved deeper and tilted towards the axis of the Ajdabiya Trough to establish the present structural configuration of the basin (Fig. 1).

The most important significance of the late Tertiary major subsidence is the oil generation, migration, and accumulations which occurred after this tectonic event (Roohi, 1996a). Therefore, seismic analyses of the complicated structural

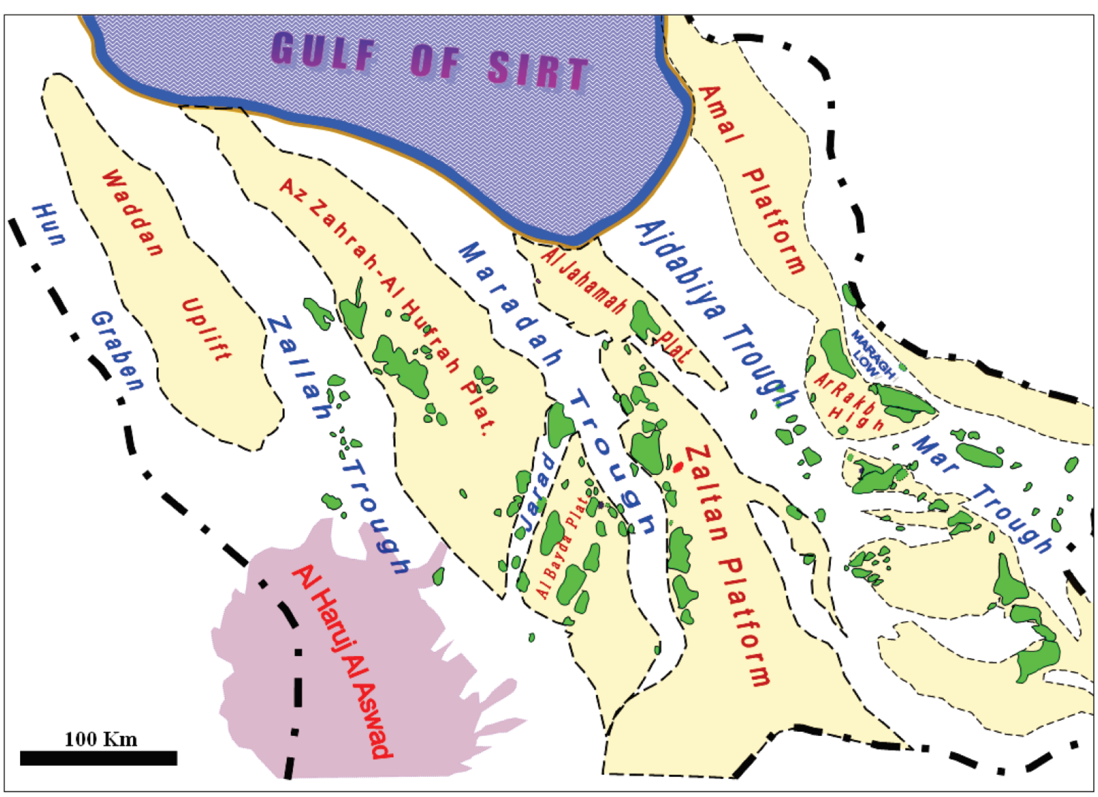

Fig.1. Sirt Basin, structural elements.

relationship of the shallow and deep horizons are challenging work for the geophysicists in prospect evaluations in the deep areas as well as along the edges of platforms.

STRUCTURAL HISTORY AND DEFORMATION OF SIRT BASIN

Figure 2 shows the major tectonic elements in North Libya and their general regional trends. Palaeozoic basins (Ghadamis, Murzuq) and highs (Qarqaf Arch, Tibisti Arch) have NE-SW trends. Subsurface data indicate that Ghadamis and Murzuq basins had plunged northeastward and ended in the western margin of the Sirt Basin; meanwhile, the northeastward continuation of the two uplifts of Qarqaf and Tibisti shows that further to the east they were joined together and had created Sirt Arch.

The Sirt Arch was broken by a series of NW-SE trending faults in Lower Cretaceous time and gradually the area collapsed into a series of alternating northwest-southeast trending horsts (platforms) and grabens (troughs). This drastic change in the structural framework of the area resulted in the initiation of the Sirt Basin superimposed on NE-SW trending Palaeozoic tectonics.

The Cretaceous structural deformation in the Sirt Basin was followed by Cenomanian marine transgression and a thick sequence of Upper Cretaceous-Tertiary shallow marine shales and carbonates associated with evaporites and sands were deposited. Horsts remained relatively stable, while the grabens, accompanied by syndepositional fault movements, subsided to a depth in excess of 6000 metres in the deepest part of the basin, filled with marine sediments.

The major tectonic features in the broad western flank of the Sirt Basin are: (from west to east) Hun Graben, Waddan Uplift, Zallah Trough, Az Zahrah-Al Hufrah Platform, Maradah Trough, and Zaltan Platform. Ajdabiya Trough is in the axial position, and the strongly fault controlled smaller horst and graben blocks, including Amal Platform, Ar Rakb High, Maragh Low, Jalu-As Sarir Structural High, and Mar Trough comprise the narrow eastern flank of the asymmetrical Sirt Basin. These horsts and grabens extend from onshore areas northwestward into a complex offshore terrain (Fig. 1).

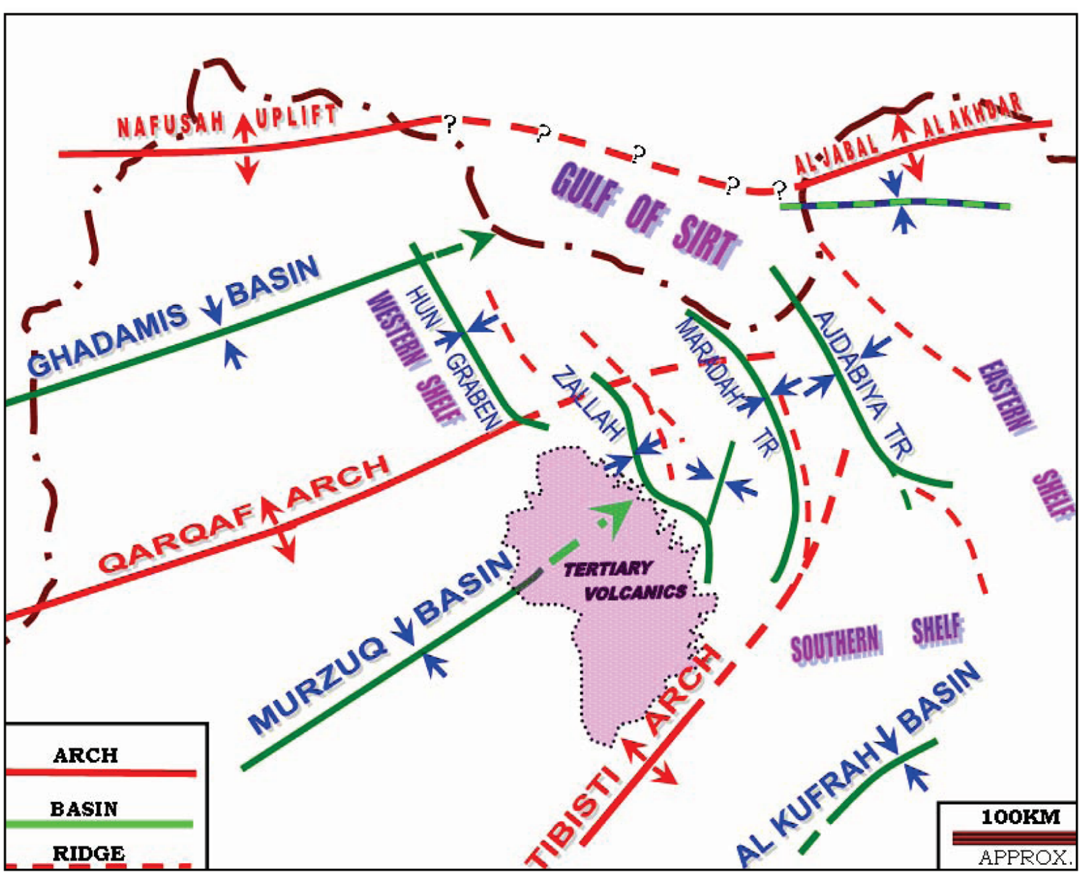

Fig. 2. Major tectonic elements, North Libya (compiled from different sources).

A significant down warping movement took place rather abruptly during the Late-Eocene to Oligocene time and the present-day asymmetrical structural configuration of the Sirt Basin is the result of this major late Tertiary subsidence.

LATE TERTIARY SUBSIDENCE AND TILTING

A regional study was carried out over the Az Zahrah-Al Hufrah Platform in the Western Sirt Basin to evaluate the Waha Oil Company concessions. The conclusion of this study was that the eastern edge of the platform (along the western edge of Maradah Trough) was structurally higher than the western edge during the deposition of Upper Cretaceous-Tertiary formations (Fig. 3). Presently their structural situations are completely reversed and the Az Zahrah-Al Hufrah High has a superior structural position in the region (Fig. 4). Detailed study of tectonic history of the area has shown that this structural deformation happened after Eocene time in which the entire platform was tilted towards east-northeast (Fig. 5), towards the axis of Ajdabiya Trough; and a favorable condition for upward hydrocarbon migration from the Maradah Trough to the present position of giant fields of Az Zahrah-Al Hufrah and Bahi were created (Roohi, 1996b).

The results of the Az Zahrah-Al Hufrah Platform study were applied to the other major tectonic features in the Sirt Basin. All the platforms, as well as all troughs, had a very similar tectonic history, and they all were subsided progressively deeper and tilted towards the axis of the Ajdabiya Trough in post Eocene time (Figs. 6-7). Of course, with the exception

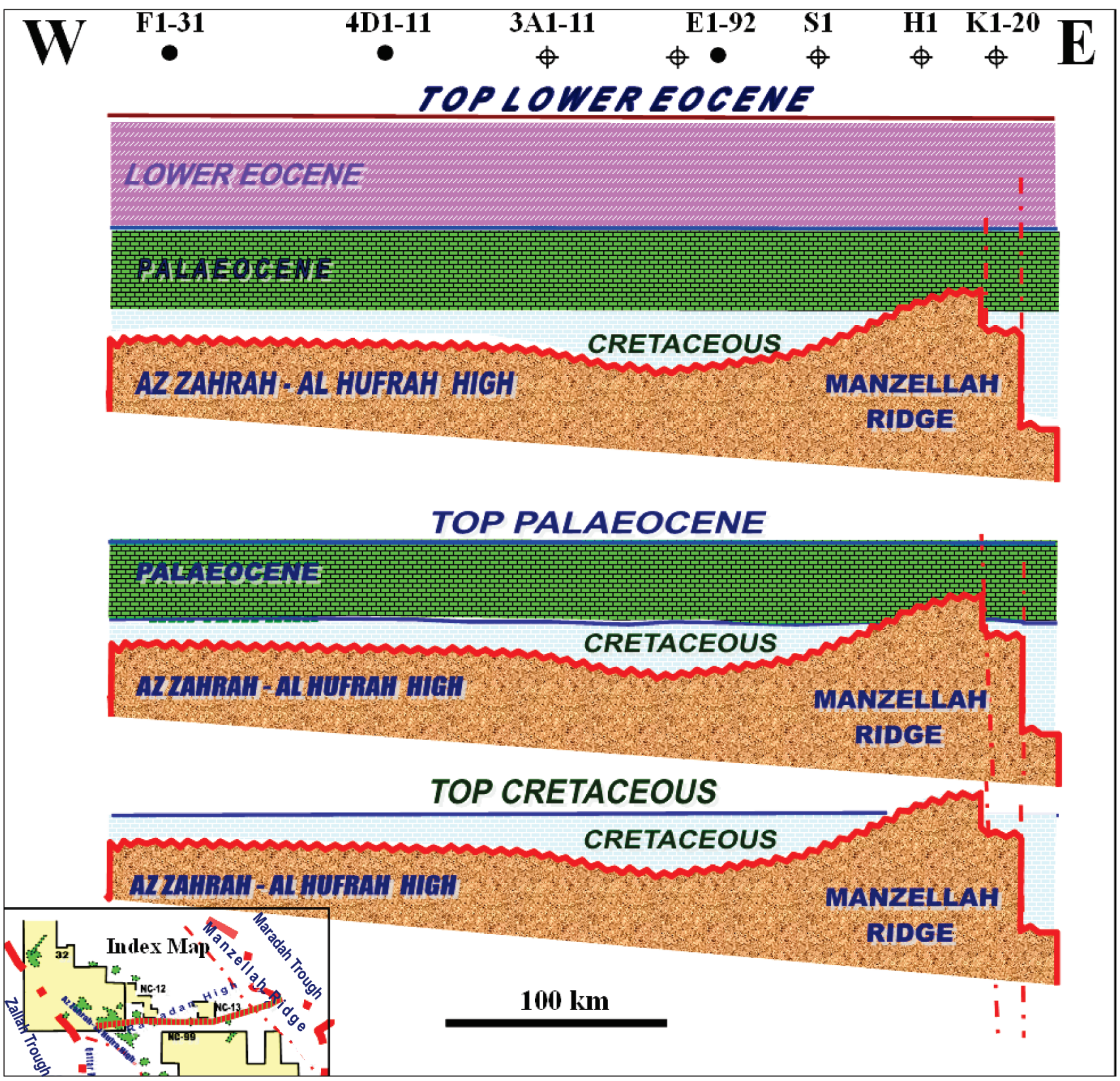

Fig. 3. Az Zahrah-Al Hufrah Platform, historical development.

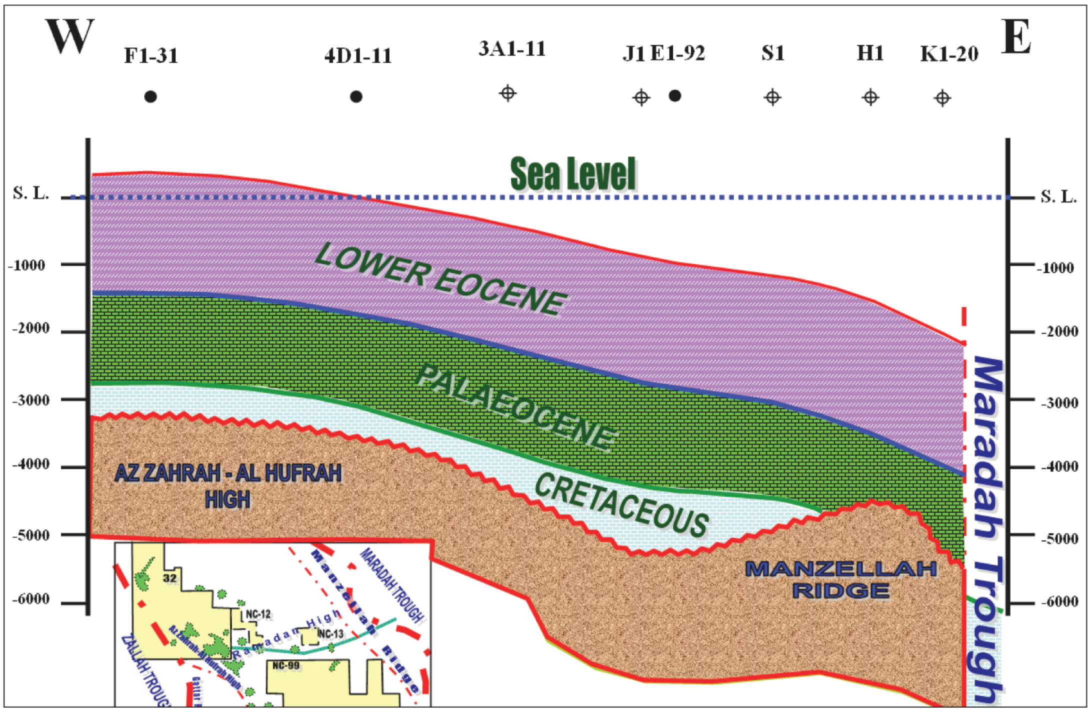

Fig. 4. Az Zahrah-Al Hufrah Platform, present configuration.

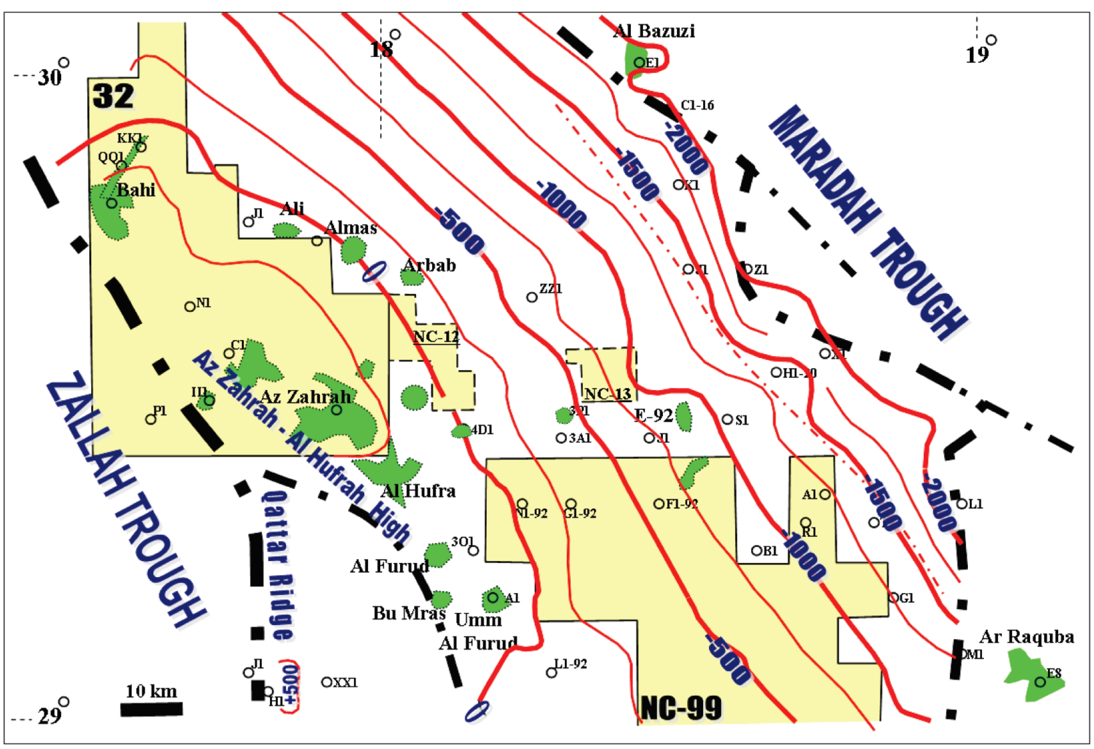

Fig. 5. Az Zahrah-Al Hufrah Platform, structure top Lower Eocene Gir Formation (C.I.=250 ft.).

of Zallah Trough in the western Sirt Basin, the pictures of the troughs are more speculative due to the lack of deep drillings in the trough areas. However, by taking into account the total post Eocene picture of the basin (Fig. 8), it is reasonable to believe that troughs have gone through the same history as the platform areas.

One significance of late Tertiary subsidence and tiltings of the Sirt Basin is that the prolific rich marine shales of Upper Cretacous age, developed

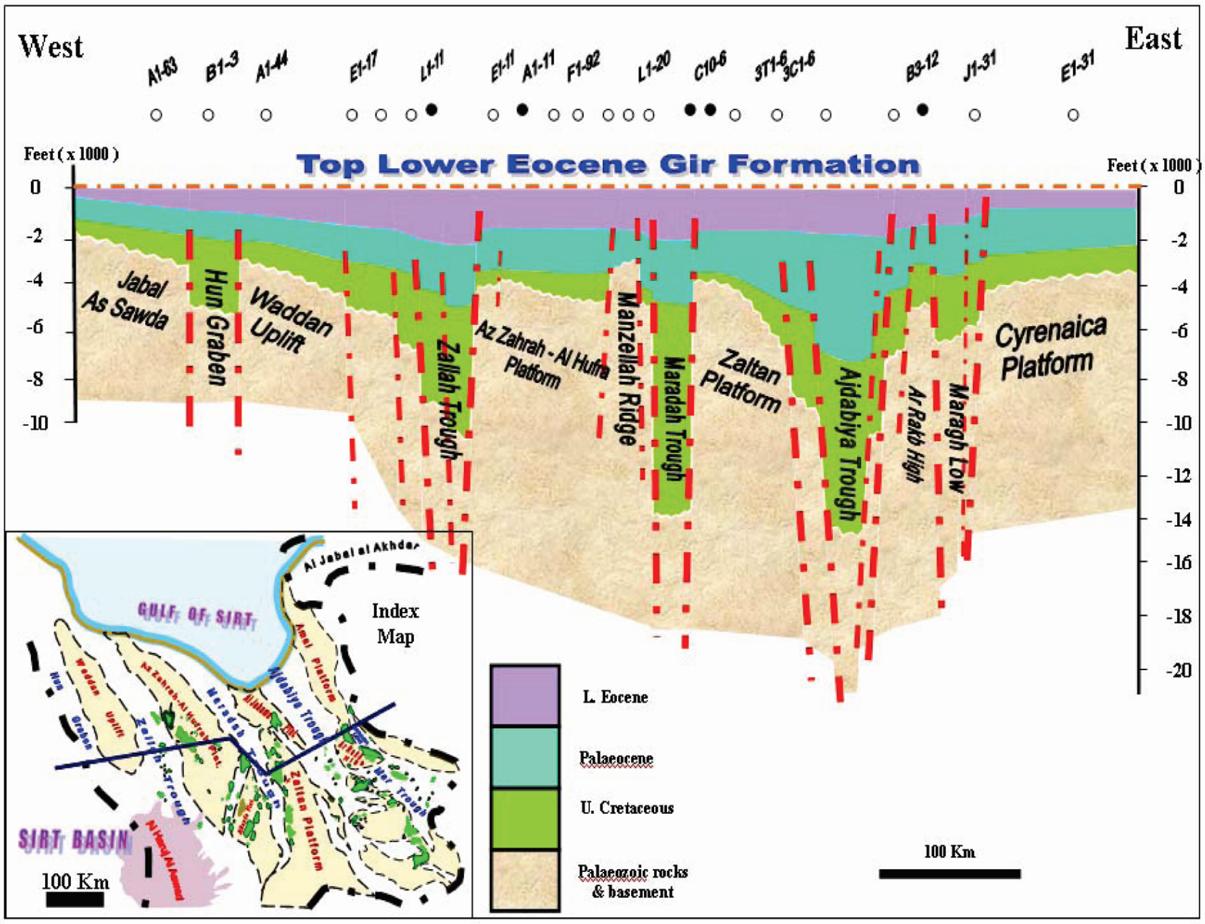

Fig. 6. Regional cross-section across the Sirt Basin leveled to top Lower Eocene Gir Formation.

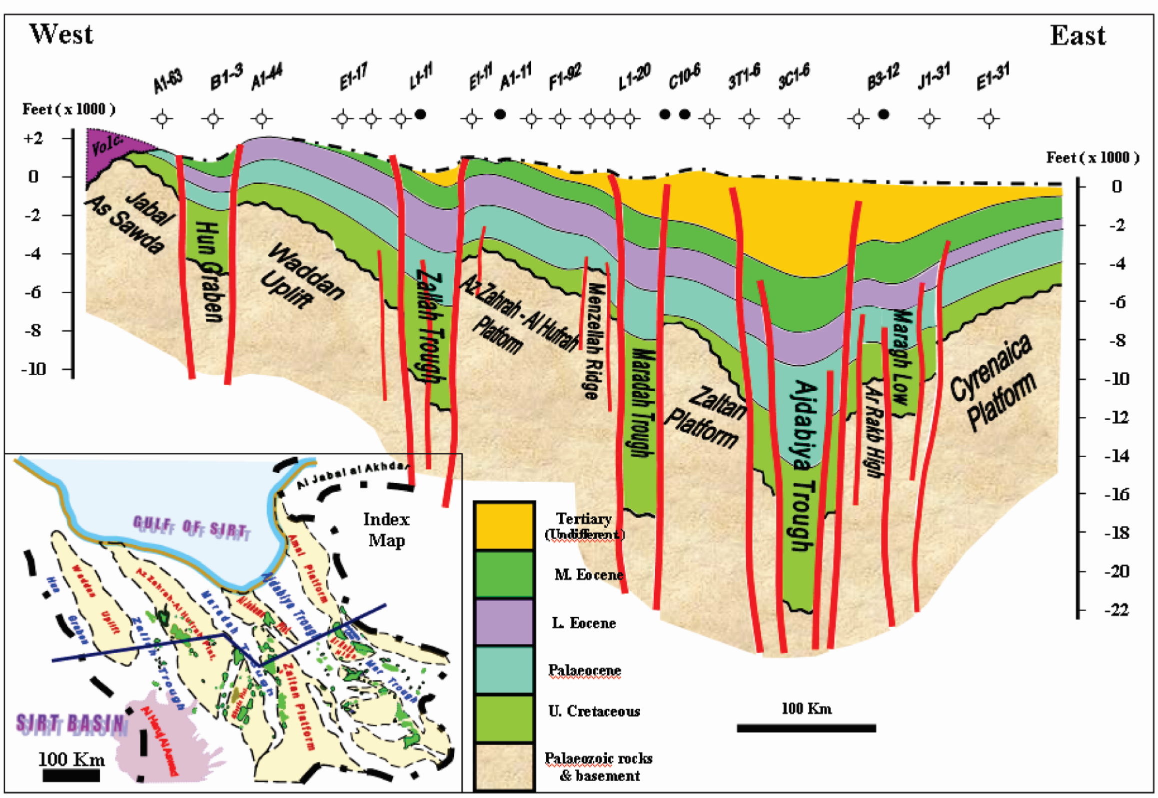

Fig. 7. Regional cross-section across the Sirt Basin, showing present picture.

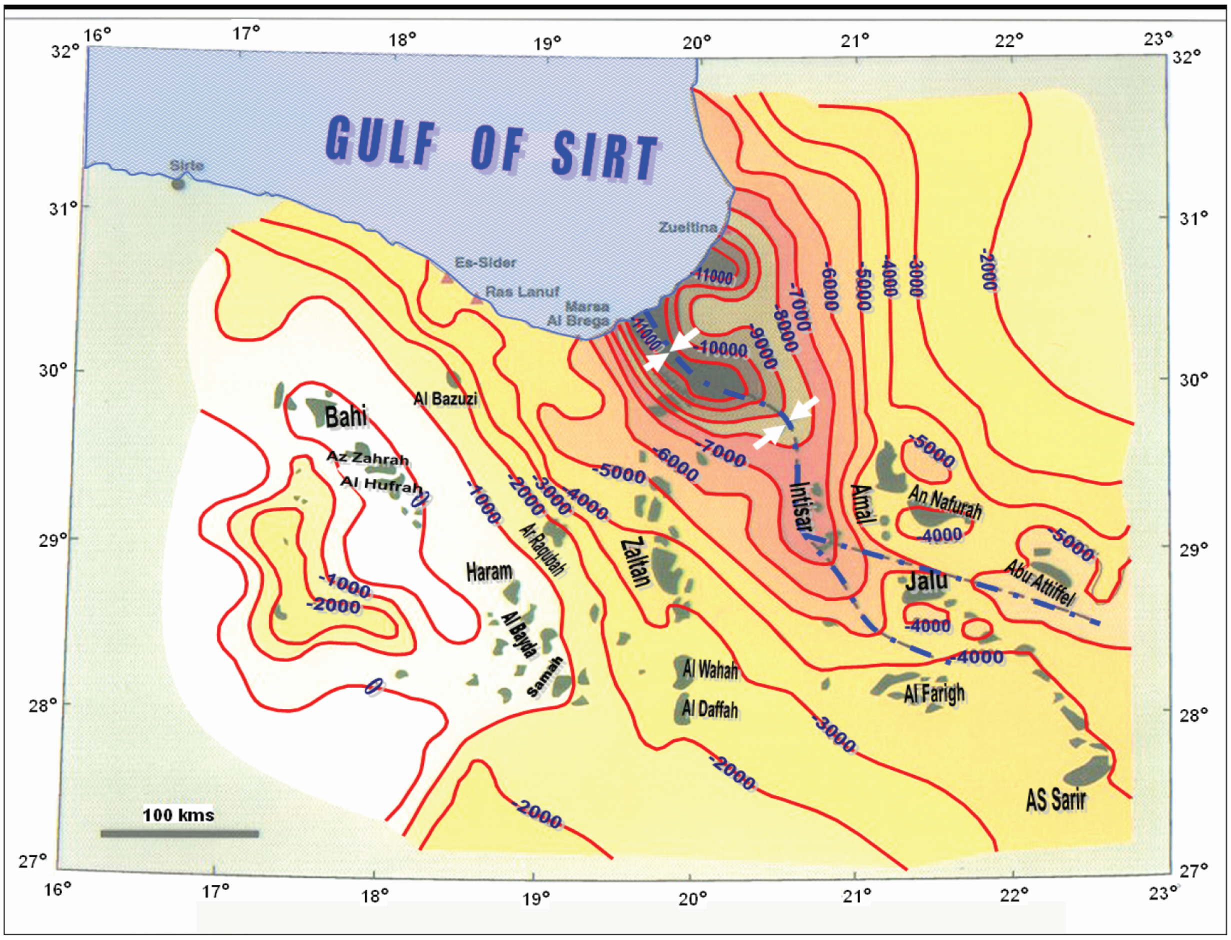

Fig. 8. Sirt Basin, structure top Lower Eocene Gir Formation (C.I. =1000 ft.).

in the troughs as the petroleum source rocks, reached the depth of hydrocarbon generations below 10,000 feet. Geochemical modeling of source rocks in the Sirt Basin shows that the peak of oil generation was during the Oligocene-Miocene (Figs. 9-11), after the major late Tertiary subsidence; and the migration happened later in post Oligocene time. Hydrocarbons generated in the deep trough areas migrated up onto the platforms and into the multiple age reservoirs. Block faultings also resulted in placing the deep clastic reservoirs in juxtaposition with mature source rocks in the deep trough areas. Major faults, with periodic reactivation, were acting as conduits for vertical hydrocarbon migration in the Sirt Basin.

SEISMIC SIGNATURES

Structural deformation of the Sirt Basin from pre-Eocene to post-Eocene picture (see Figs. 6 and 7) requires considerable differential movements between platforms and troughs along the bounding faults; and different magnitudes of subsidence to comply with the present structural configuration of the basin. Figure 7 clearly shows the tilings of all the platforms as well as troughs towards the axis of Ajdabiya Trough due to this major late Tertiary subsidence.

A series of available seismic lines, from only the Waha Oil Company concessions, are provided to see some of the seismic signatures of these late Tertiary tectonic events such as: tiltings; differential block movements; and lateral compressional forces in the shallow horizons of the trough areas.

An E-W trending seismic line covers the Az Zahrah-Al Hufrah Platform and clearly shows the northeastward post-Eocene tilting towards the axis of Ajdabiya Trough (Fig. 12). Unfortunately, the line does not extent into the Maradah Trough to the east, and therefore, the situation of the eastern margin of the platform is not shown. However, structural complications as well as indications of missing formation at depth, along the eastern margin, can be observed.

Figure 13 shows a seismic line of the structural configurations of Az Zahrah-Al Hufrah Platform with the Zallah Trough to the west. Re-activation

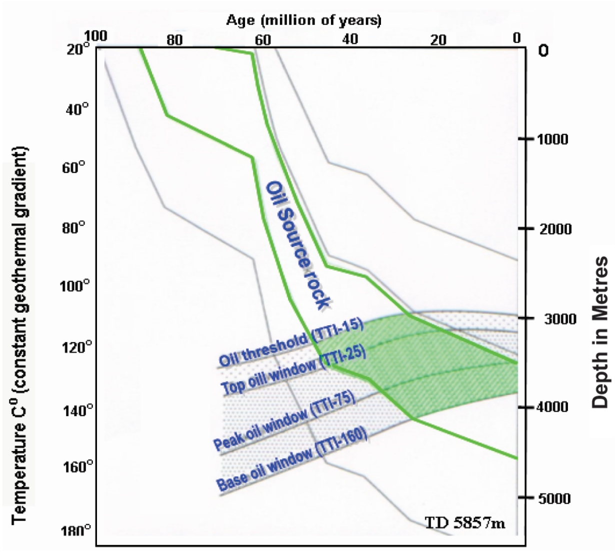

Fig. 9. Time-temperature index of maturity (TTI), well 5P1-59.

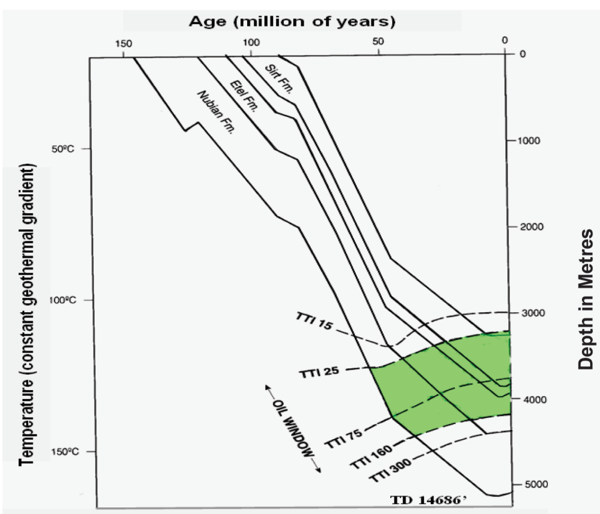

Fig. 10. Burial history (TTI), well DD2a-59.

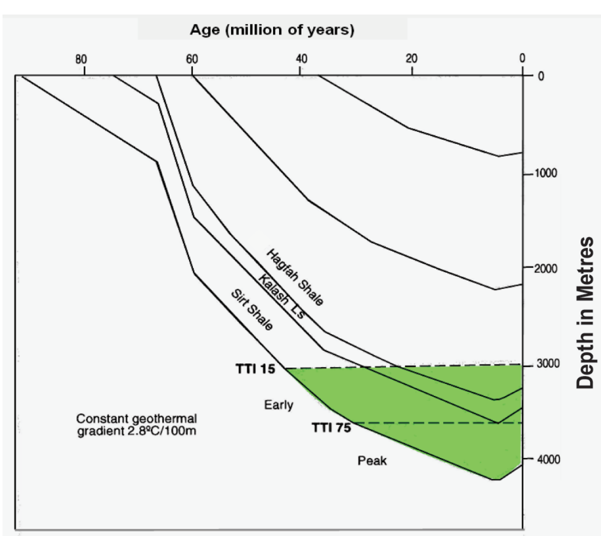

Fig. 11. Burial history (TTI), Maradah Trough, adjacent to Ar Raguba Field.

of the major bounding fault (Az Zahrah Fault) with huge differential movements in Late Tertiary time together with the northeastward tiltings of both Az Zahrah-Al Hufrah Platform and Zallah Trough, exerted a lateral compression over the shallow horizons in the trough area.

Shale, anhydrite, and salt in the Eocene formation; have created,under the localized lateral compression, different structures in comparison with the deep formations.

A northeast-southwest trending seismic line from Concession 31 in the western margin of the Amal Platform in the eastern flank of the Sirt Basin is presented in Figure 14. It clearly shows the post Eocene westward tilting of the platform towards the Ajdabiya Trough.

To comply with the present picture of the Sirt Basin; late Tertiary tilting in the eastern flank of the Sirt Basin is in the opposite direction of western flank (Fig. 15).

Jarad is a narrow trough, along the NE-SW trending palaeo-tectonic feature, separating the Az Zahrah-Al Hufrah Platform from its southeastern extension called Al Bayda Platform (Fig. 1). An E-W trending seismic line across this narrow trough is shown in Figure 16. During the late Tertiary tilting, the two platforms of Az Zahrah-Al Hufrah and Al Bayda did not tilt exactly at the same direction and/or same magnitude. Compared to the Al Bayda Platform, Az Zahrah-Al Hufrah underwent a higher angle of tilting. It seems that the magnitude of tilting and subsidence of different platforms and troughs are related to the depth variation of the Ajdabiya Trough. Ajdabiya Trough becomes gradually shallower towards the southeast and tectonic blocks in the Sirt Basin follow the same picture.

Considering the differential movements between the Az Zahrah-Al Hufrah and Al Bayda platforms, the tilting of the Az Zahrah-Al Hufrah towards the northeast and Al Bayda Platform with different angle and less magnitude of subsidence towards east-northeast a localized lateral compressional force was created in the Jarad Trough area and different structural pictures between the shallow and deep horizons were developed.

There are several potential oil fields on the Al Bayda Platform, all of which are controlled by faults of different magnitudes. Major faults trend NE-SW, more or less parallel to the Jarad Trough, and were possibly created by the reactivation of pre-Upper Cretaceous faults in late Tertiary time. These major

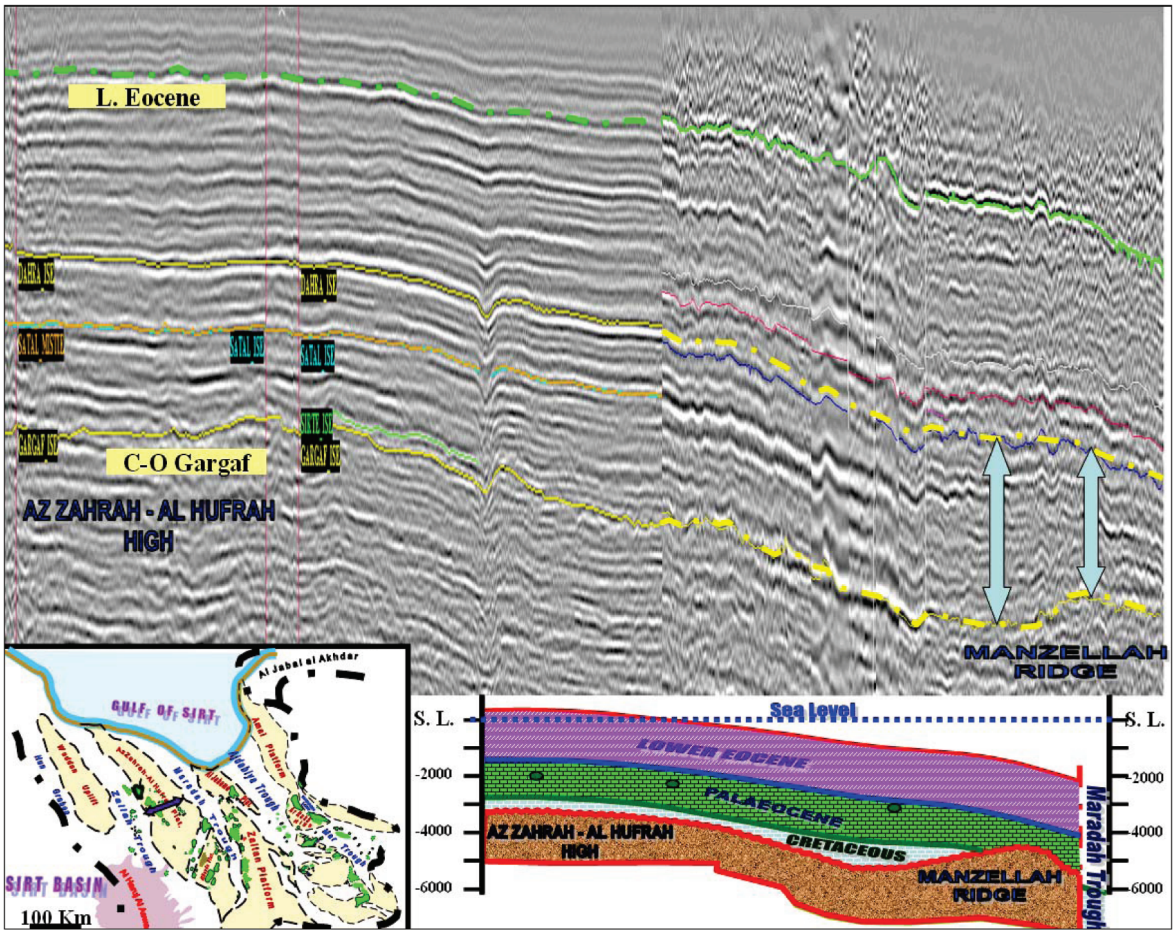

Fig. 12. E-W trending line across the Az Zahrah-Al Hufrah Platform.

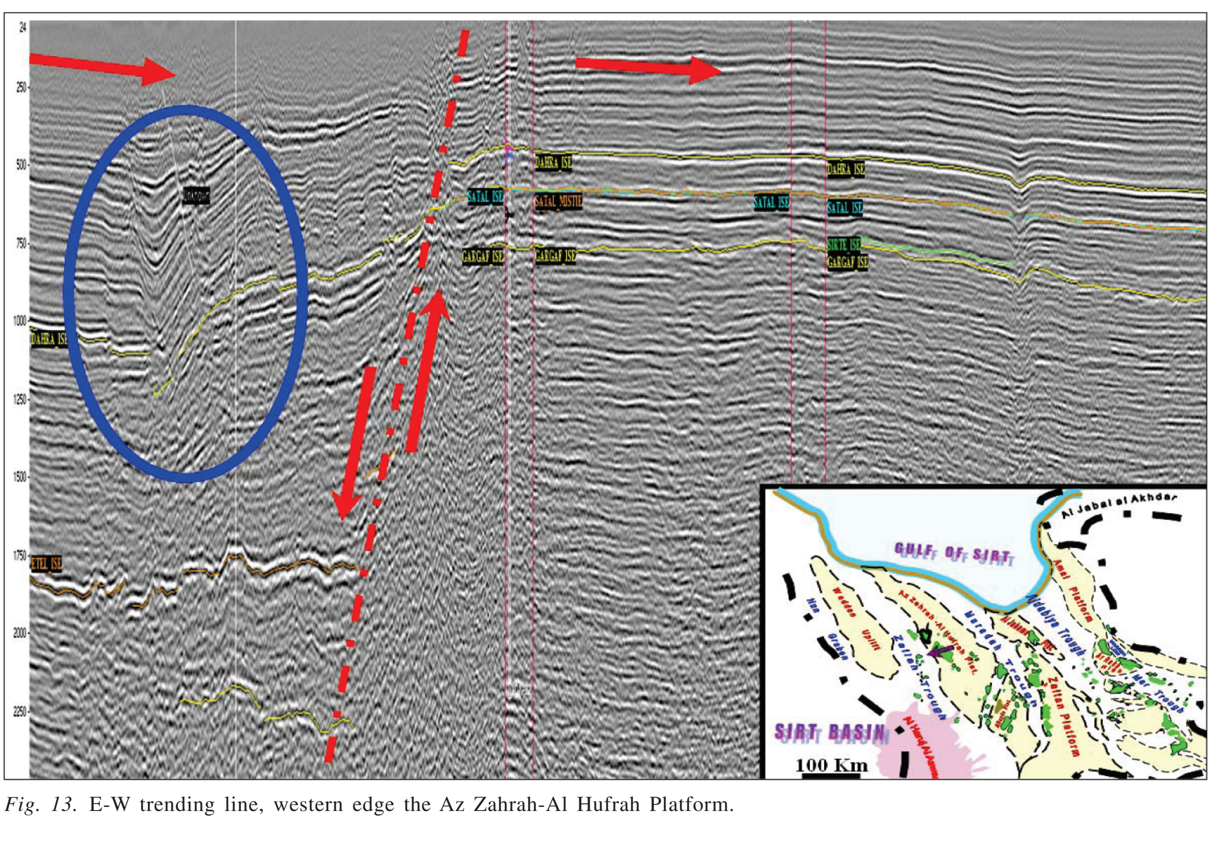

Fig. 13. E-W trending line, western edge the Az Zahrah-Al Hufrah Platform.

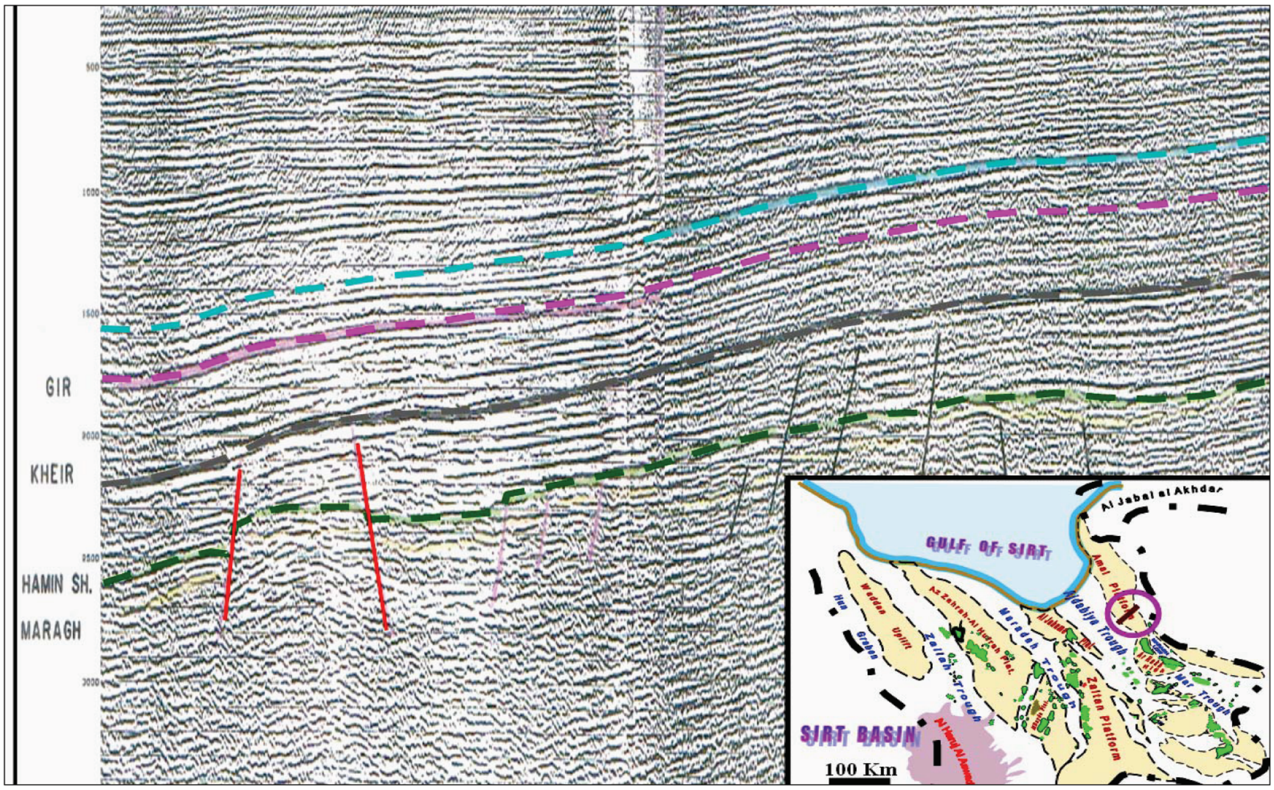

Fig. 14. NE-SW trending line, Concession 31, Amal Platform.

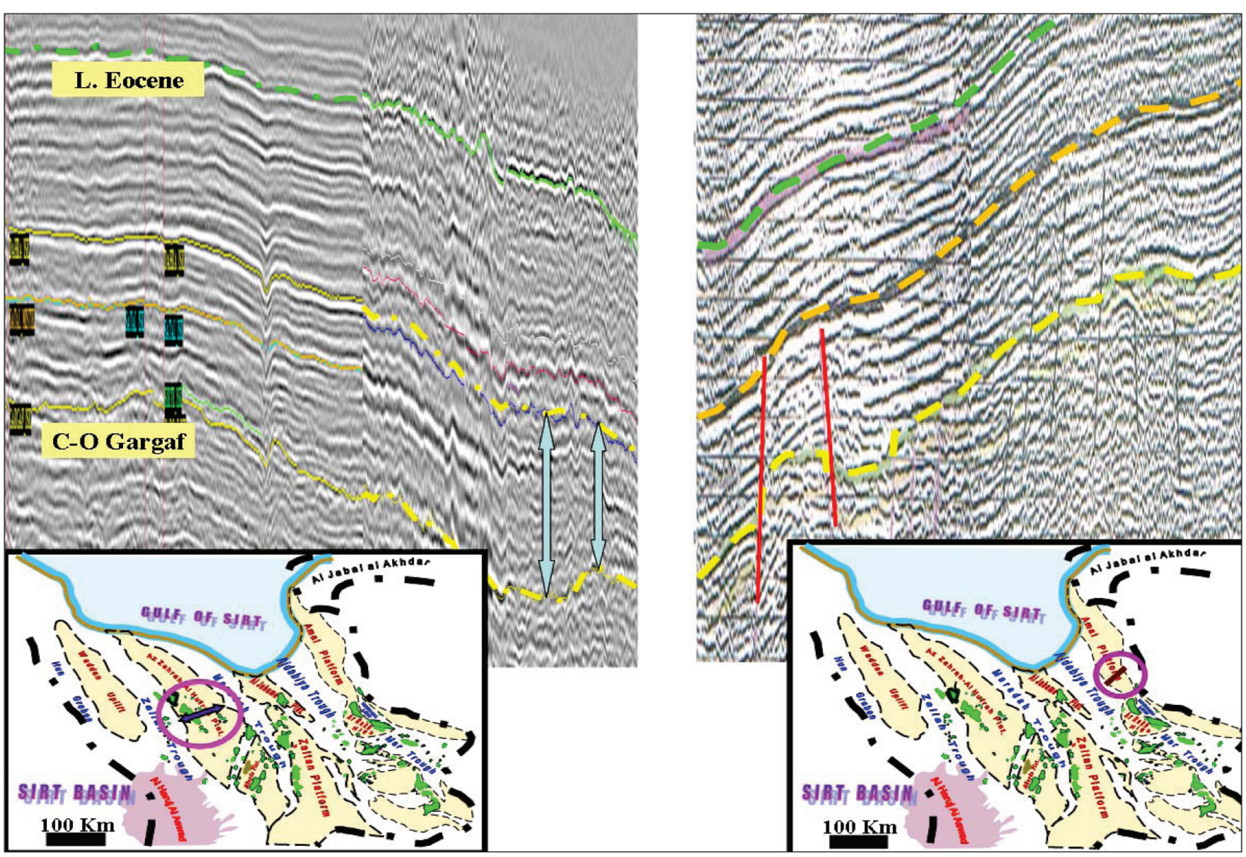

Fig. 15. Direction of tilting of Az Zahrah-Al Hufrah and Amal Platform, towards the axis of the Ajdabiya Trough.

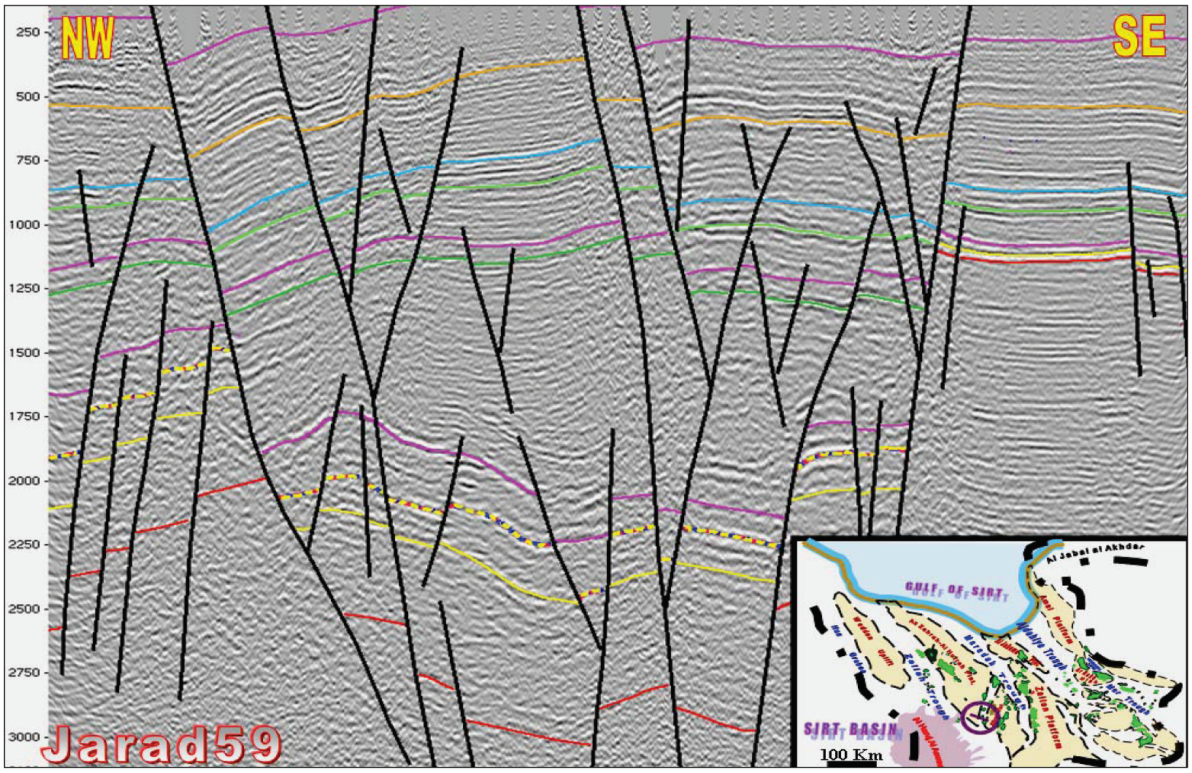

Fig. 16. NW-SE trending line across the Jarad Trough.

faults are mostly right lateral and associated with echelon faults.

The following maps (Fig.17a) are from the area, just to the northeast of Balat field on the Al Bayda Platform (AA structure). The coherency display map at the level of Lower Eocene Gir Formation shows the same fault pattern of Lower Palaeocene Beda producing pay. This indicates that during the east-northeastward late Tertiary tilting, Al Bayda Platform was broken into several blocks along the NE-SW trending pre-Upper Cretaceous faults.

To comply with present structural picture of the Sirt Basin, northwest blocks of the Al Bayda Platform moved farther and tilted more towards the Ajdabiya Trough compared to southeastern blocks. These right lateral faults systems (strike slip faults) seems to be the result of differential block movements.

This NE-SW trending seismic line (Fig.17b) covers the eastern block of the above map and clearly shows the late Tertiary northeastward tilting.

Although Figure 18 covers a very small portion of the eastern edge of the Al Bayda Platform (Zaggut Field), it clearly shows the northeastward late Tertiary tilting as well as the complications along the eastern platform bounding fault with the Maradah Trough.

Figure 19 is a NE-SW trending seismic line across the giant field of Al Wahah, along the western edge of the Zaltan Platform. The late Tertiary northeastward tilting of the platform is apparent. The western platform bounding fault with the Maradah Trough to the west is indicated in this seismic line as well.

This line is in a similar structural position as the western edge of the Az Zahrah-Al Hufrah Platform with the Zallah Trough (Fig. 13). However we do not see the crumbling picture of the shallow horizon in the trough. The reason is that here we do not see a huge late Tertiary reactivation of the bounding fault; and also because of the narrowness of the Maradah Trough, formations did not have room to subside in relation to the Zaltan Platform. Therefore, the compressional force created in the Zallah Trough due to the differential movements between the platform and trough does not exist in this area.

Both Zaltan Platform and Maradah Trough are tilted almost uniformly together towards the axis of the Ajdabiya Trough. The structural map of the Gir Formation covering the Sirt Basin (Fig. 8) shows only a small indication of the Maradah Trough.

The seismic line across the giant field of Al Daffah, along the western edge of the Zaltan Platform (Fig. 20) exhibits a similar tilting as Figure 19. It is tilted towards northeast and complicated along the edge of the platform. There are some indication of late Tertiary structural lineaments (slump feature); perhaps created by the

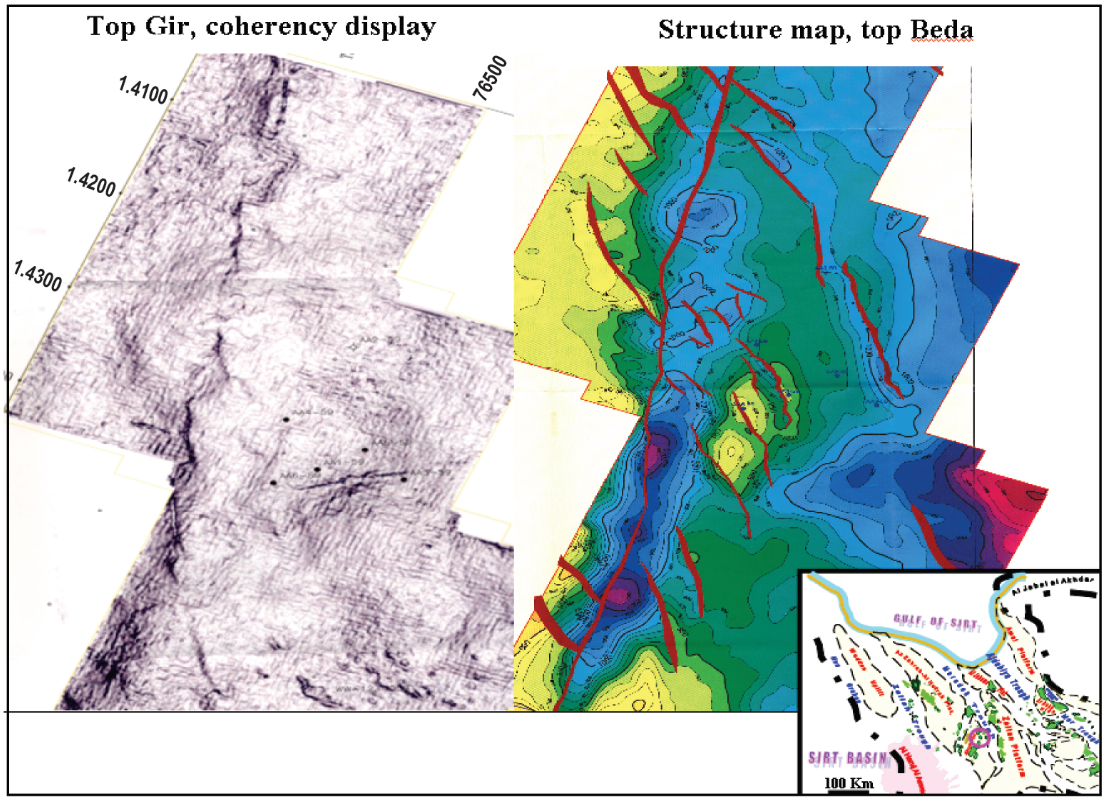

Fig. 17a. Al Bayda Platform, North Balat area, "AA" structure.

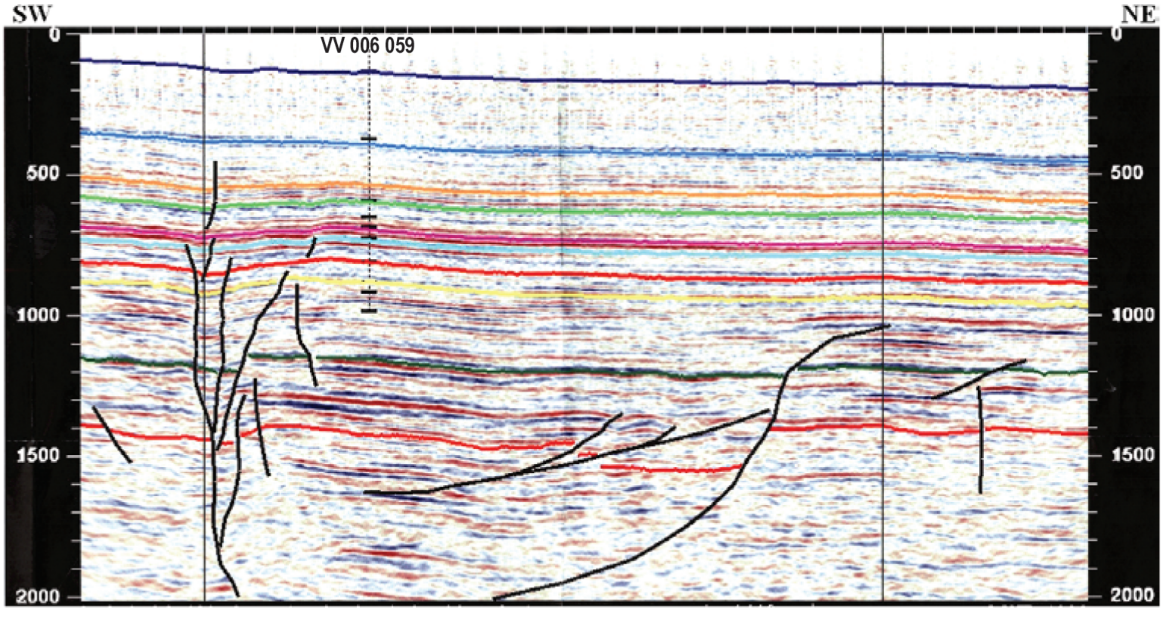

Fig. 17b. NE-SW trending line, North Balat area.

reactivation of NE-SW trending pre-Upper Cretaceous faults.

The seismic lines presented in Figures 21a and 21b are from the eastern edge of the Zaltan Platform (Harash Field). Although they cover only a very small portion of the platform area; they clearly show the northeastward late Tertiary tilting, towards the Ajdabiya Trough.

A complicated picture along the eastern edge of the Zaltan Platform, in the Harash Field is shown in Figure 21a. It is clear that at the time of deposition of the Upper Cretaceous formations the area along the edge was structurally higher, overlain by thinner formations. Only after the late Tertiary tilting (Fig. 21b), was this superior structural situation lost (similar to the Az Zahrah-

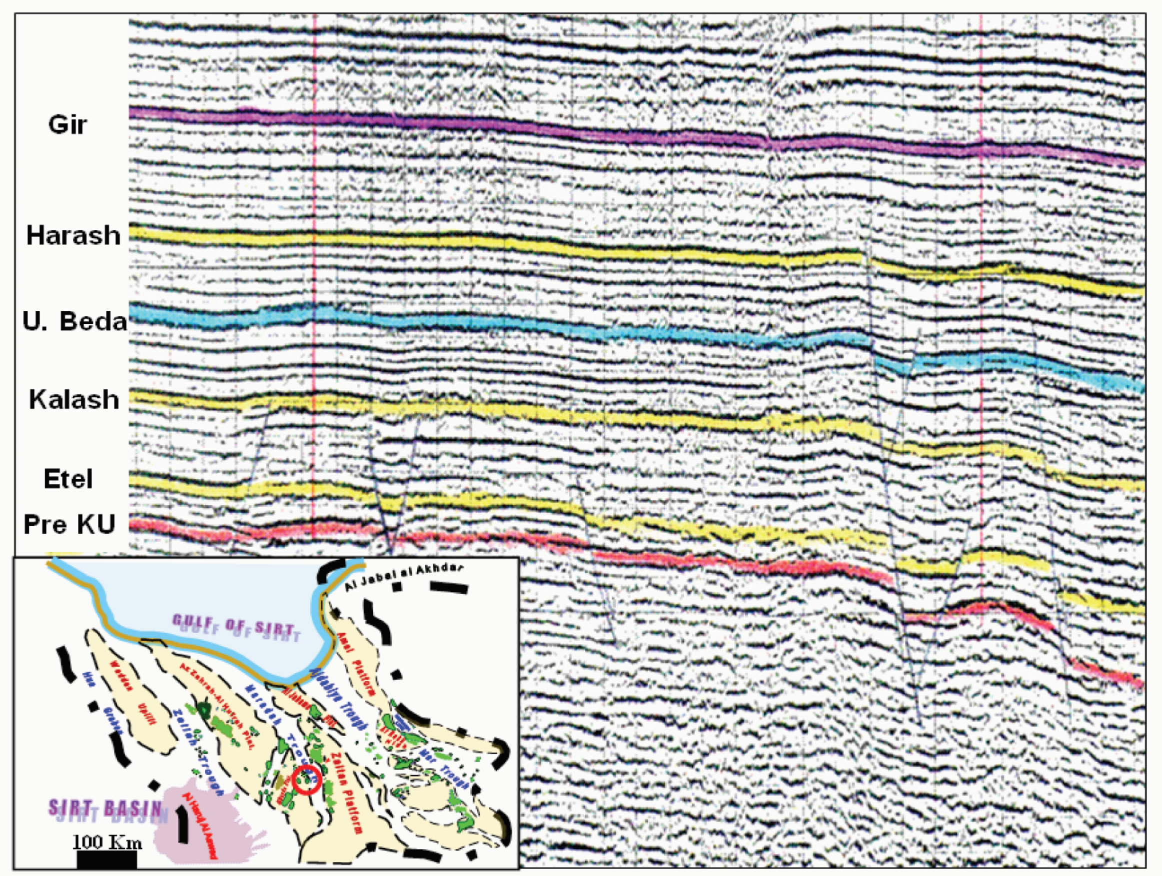

Fig. 18. NW-SE trending line, across Zaggut Field.

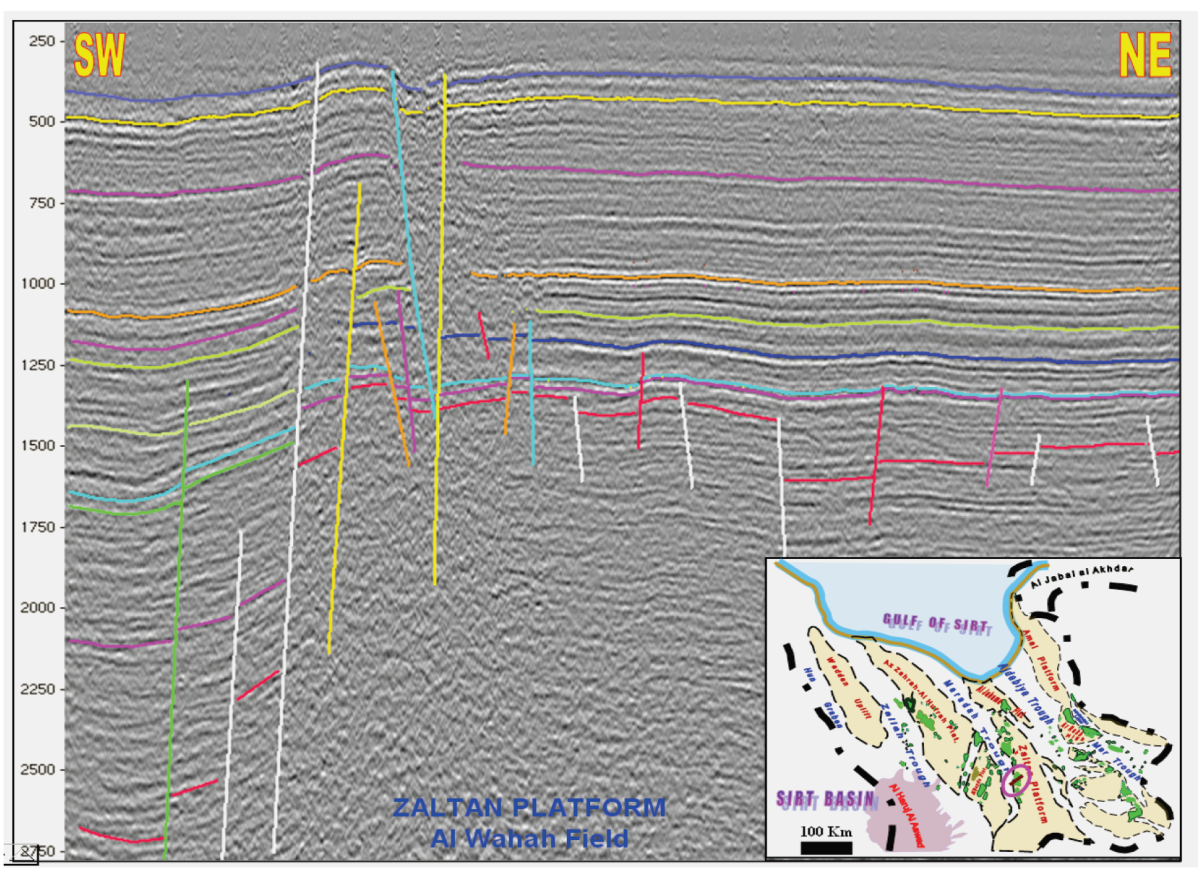

Fig. 19. NE-SW line across the Al Wahah Field, western edge of the Zaltan Platform.

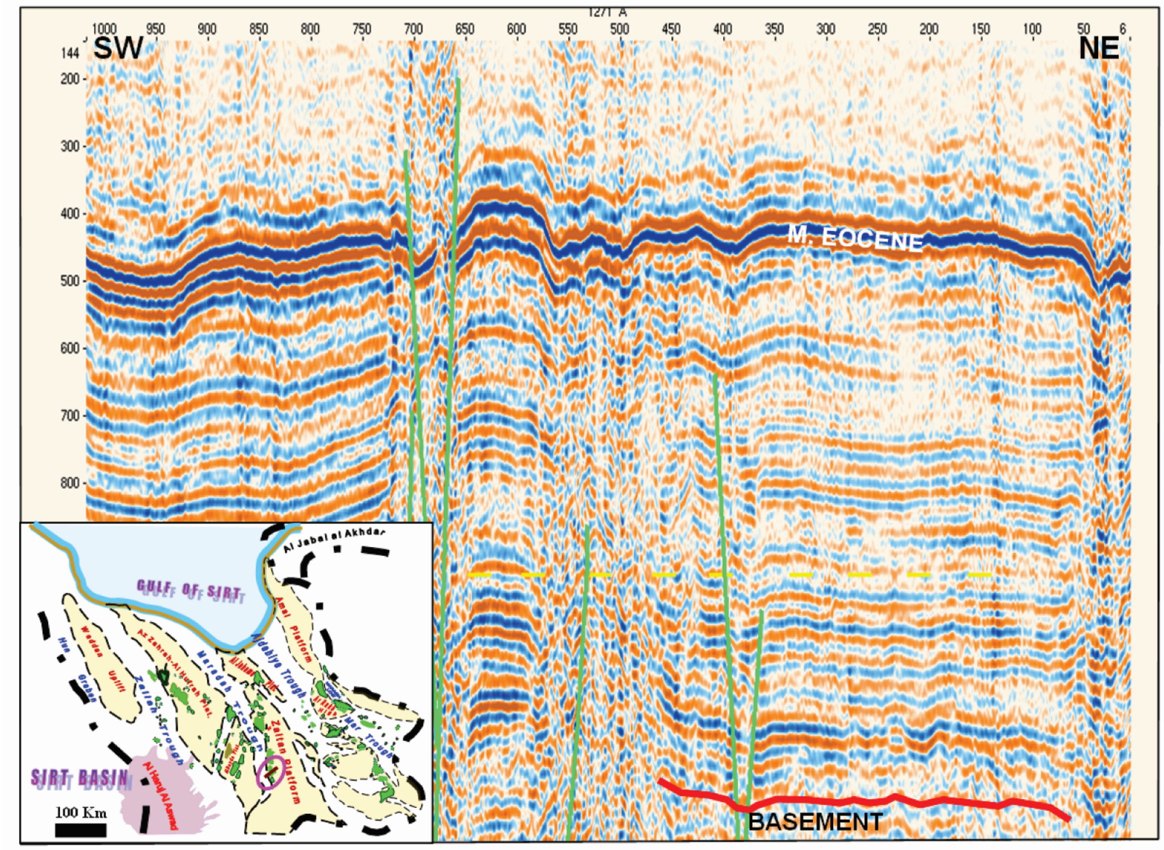

Fig. 20. NE-SW trending line across the Al Daffah Field, western edge of the Zaltan Platform.

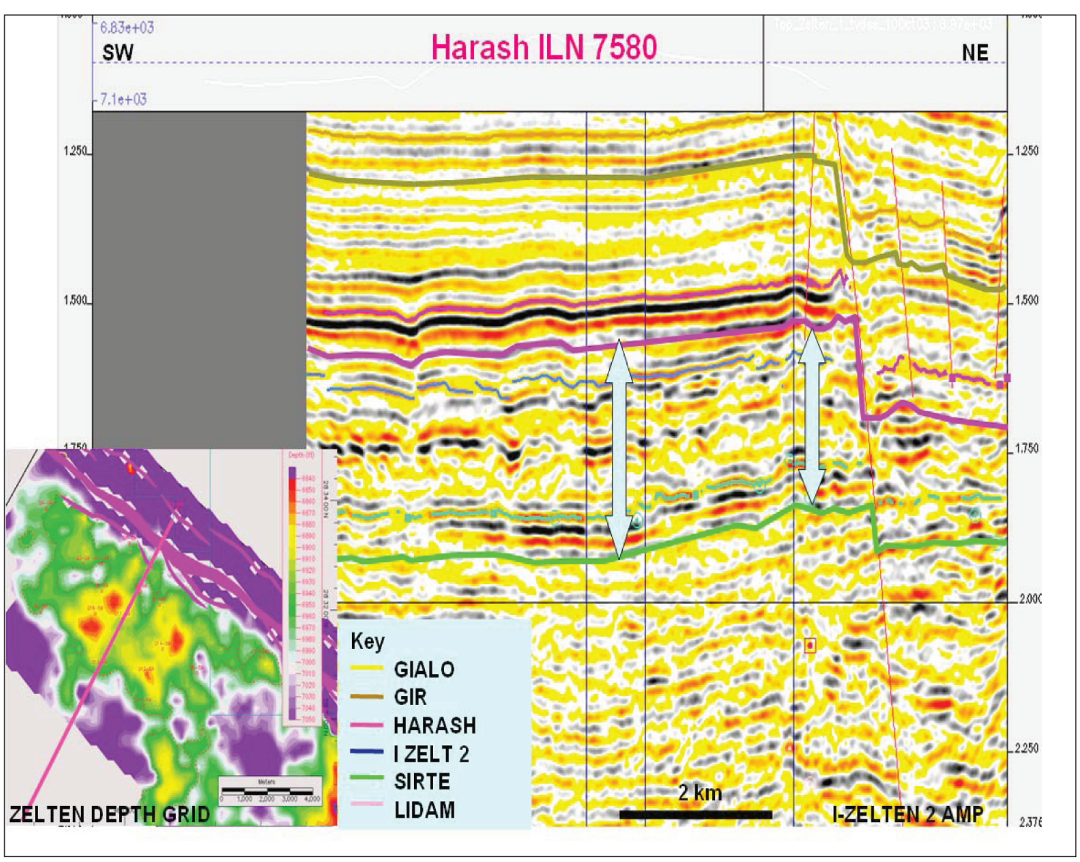

Fig. 21a. NE-SW trending line, Harash area, eastern edge of Zaltan Platform.

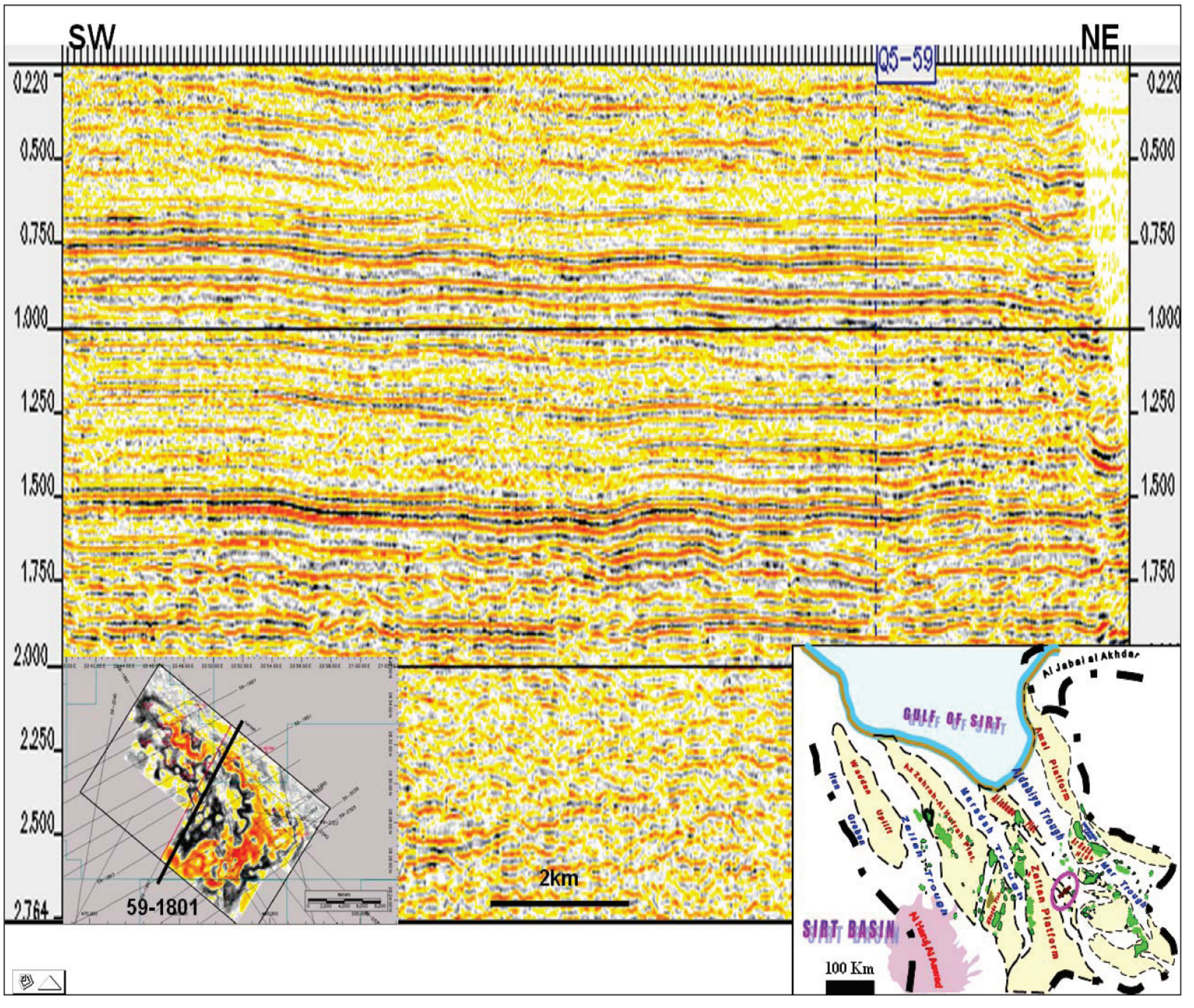

Fig. 21b. NE-SW trending line, Harash Field, eastern edge of Zaltan Platform.

Al Hufrah Platform, Fig. 12) and the present complicated picture evolved.

Another important point to note in this seismic line is the fault displacement which are more at the shallow horizons compared to the deep ones. This type of fault displacement is considered here as reversal blocks movement; which means a faulted tectonic block was higher at earlier stage and reversed its structural position later. These types of fault displacements (larger displacement at the shallower horizons) may be interpreted as strike-slip faults; but the only late Tertiary major tectonic events (subsidence and tiltings discussed in this paper) in the Sirt Basin are the most reasonable explanations for these complicated structural pictures.

Reversal block movements are observed not only along the edges of the platforms; but also are frequently seen in different magnitudes and directions in the trough areas, which make them difficult to be interpreted as strike slip faults due to a single compressional force.

Some relatively young structural lineaments, affecting all the formations of deep and shallow horizons, are observed in different parts of the Sirt Basin. These lineaments are believed to be of tectonic nature and the result of late Tertiary subsidence and tilting of different blocks.

The following seismic line (Fig. 22) shows one of these late Tertiary tectonic lineaments in the northern part of Waha's Block NC-98, along the eastern plunging nose of Rakb High, Eastern Sirt Basin.

Regional structural study of the Zaltan Platform indicates that the northern extension of the platform, called Al Jahamah Platform (see Fig. 1) is extremely complicated by the late Tertiary tectonic events, and differential and reversal block movements are expected to be very common (Fig. 23).

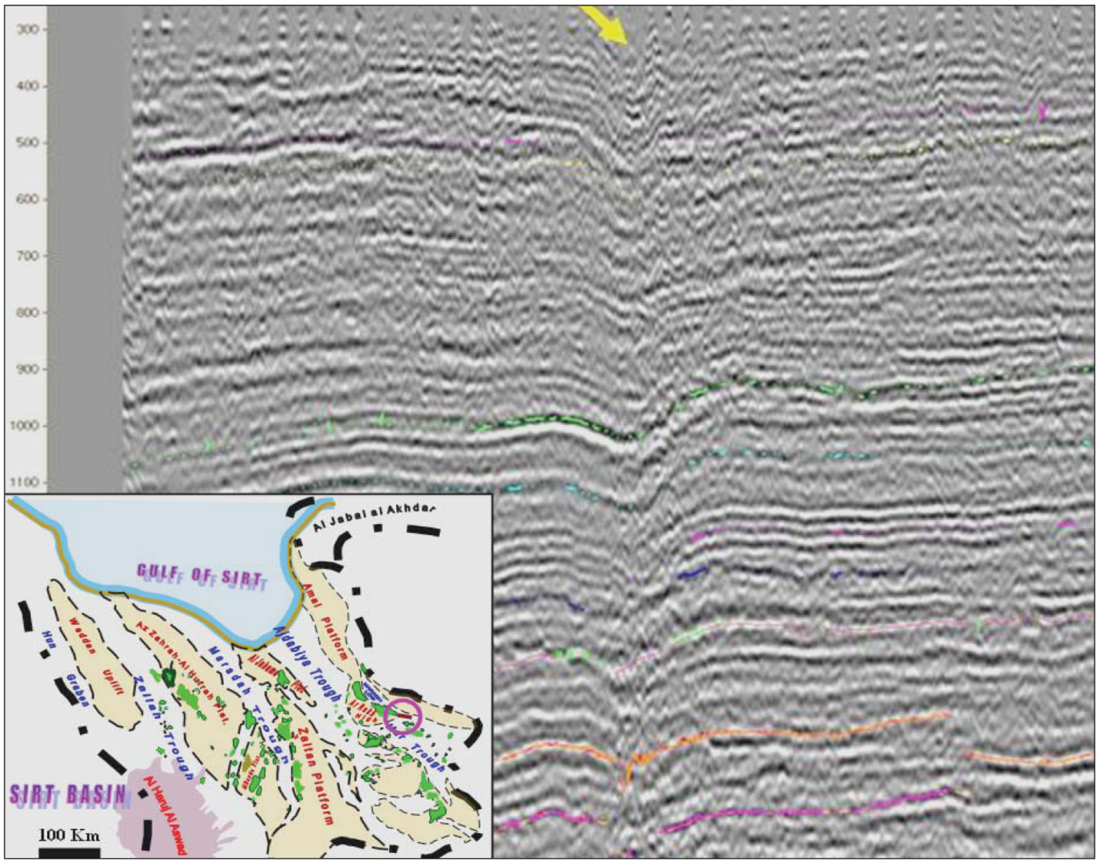

Fig. 22. Late Tertiary structural lineament, eastern nose of Rakb High.

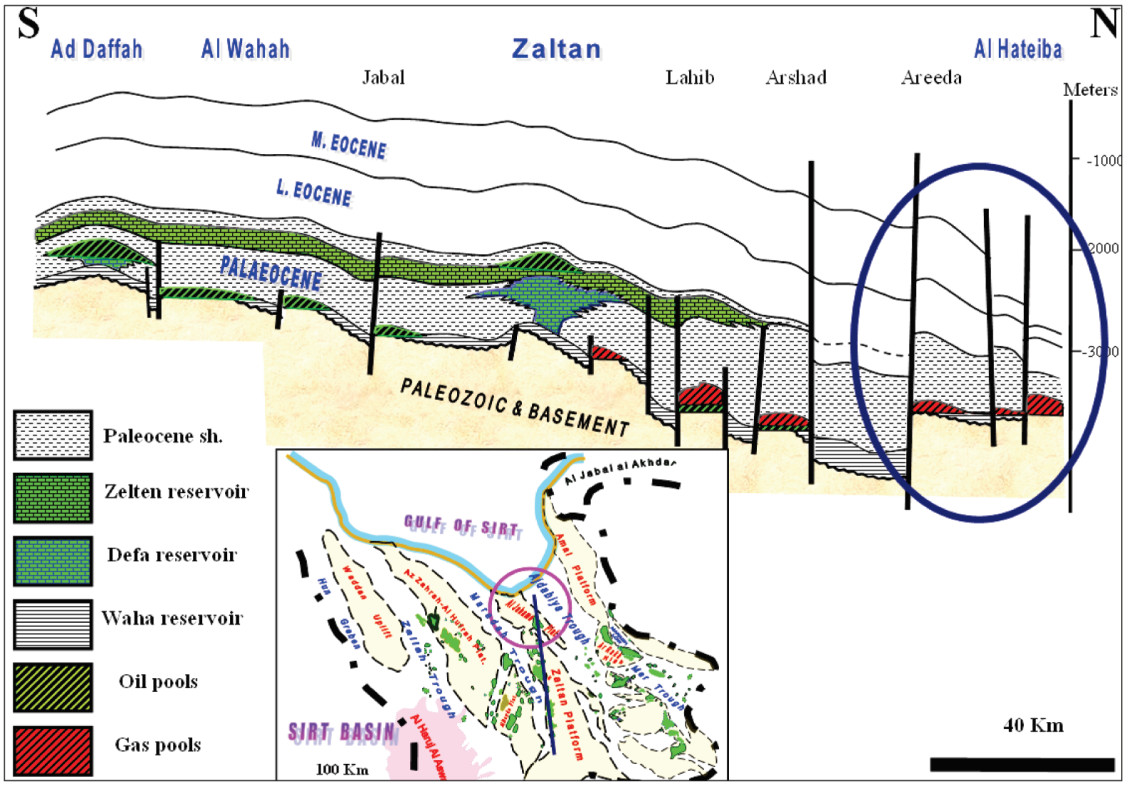

Fig. 23. N-S Regional Cross Section across the Zaltan Platform.

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