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Seismic characteristics of Palaeocene carbonate buildups in SE Ajdabiya Trough, Sirt Basin, Libya

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Abstract

The Palaeocene section in the SE part of Ajdabiya Trough in the eastern Sirtbasin consists of a carbonate platform, which developed, in response of rapid Lower Tertiary regional subsidence, which cause Deep–water conditions in the area and widespread marine transgression following Cenomanian rifting. Seismic sections show evidence of a number of carbonate plays (reef), particularly around the trough margins. The principal hydrocarbon reservoir in the study area is Upper Sabil, which is sealed by Harash lime mudstone. The integration of seismic and borehole data was used to develop a stratigraphic framework for the Palaeocene reefs in the area and interpret seismic variations caused by geological changes. Synthetic seismogram available in some wells used to identify the stratigraphy and to predict how stratigraphic variations may affect a seismic event. The synthetics were based mainly upon velocity changes since the relative effect of density is small in the majority of sediments. The tied between the seismic sections and the synthetic constructed in the borehole close to the seismic line show an acceptable agreement with small misties. The interpreted seismic sections illustrated clearly the onlap of the Harash shale on the delineation margins of the limestone buildup, consequently, the seismic facies changes between the reef and the adjacent strata identified by lateral changes in reflection properties. The reef body shows a chaotic reflection character. The established time structure maps of top Sheterat and Kheir (upper Palaoecene) sequences which below and over the reef respectively as well as the structure maps of the Eocene package both Gir (Lower Eocene) and Gialo (Upper Eocene) have indicated dip towards the north.The overlying sediments (Kheir Formation) develop a drape over the reef about 7 msec. Part of this can be attributed to depositional thinning of Kheir strata on to the reef, but the greater part is due to differential compaction, the pull–down velocity was revealed in some seismic sections cross the buildups as a result of the slower interval velocities of the sedimentpackage underneath the reef, which may relate to the high limestone porosity.

Introduction

The study area is located into the southeast of Ajdabiya trough, Sirt basin with the Rakb high to the east and Zelten platform somewhat further to the west (Fig. 1.0). During the late Palaeocene a number of isolated local seabed highs became the loci for the widely known prolific bioherms. The Palaeocene contains about $^1/_3$ of the oil discovered in the Sirt basin. The dominant lithologies are carbonate and shales, with the basin being dominated by the large Az-Zahra -Al hufrah carbonate platform in the west, and the Sabil platform in the east. The troughs are principally filled with calcareous marine shales with thin stringers of shaly limestone. The Ajdabiya trough contains about 1000 m of Palaeocene sediments (Hallet, *et al.*, 1996). Conley (1972) has described the Palaeocene transgression and facies distribution.

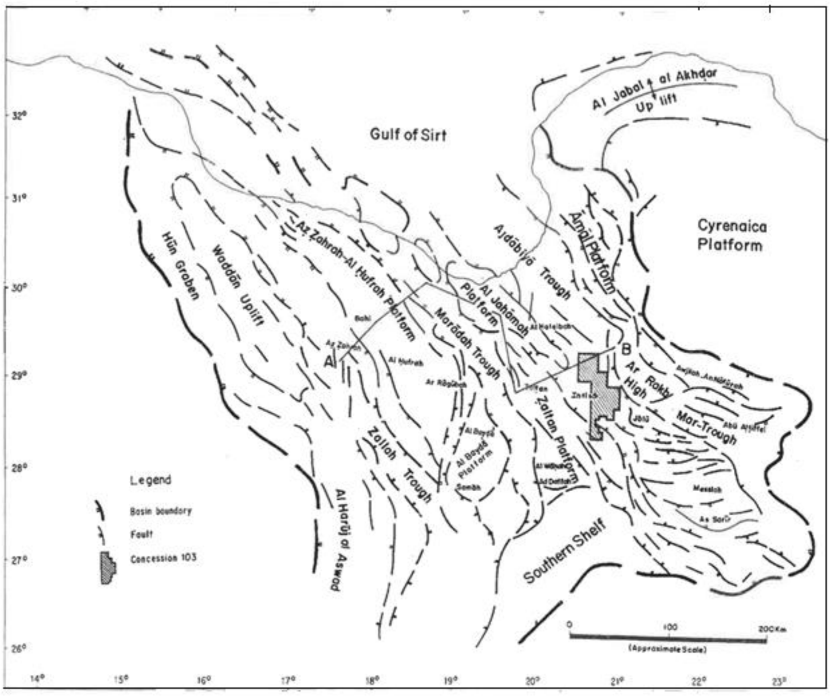

Fig. 1.0: Sirt Basin major tectonic elements and location map of study area (conc. 103).

The importance of the Palaeocene package in the Sirt basin from a hydrocarbon point of view is the presence of a number of reefs. Those reefs represent good reservoirs rich in oil such as Intisar (A, B, C, D), As Sahabi and Meherigah fields. They are located close to the margin of the trough. The development of reefs on horst blocks accentuated the effects of differential compaction, and there by influenced the accumulation of hydrocarbons of the overlying sequences (Conant and Goudarzi, 1976).
The style of carbonate sequence stratigraphy on the platform is mainly a reflection of the balance between sea-level rise and carbonate production, as summarized in a review by Jones and Desrochers (1992).

Geological setting

The Ajdabiya trough represents the largest and deepest trough in the Sirt basin.
It contains 6000 m of sediments, about 2000 m of the total sediments belong to the Miocene time. The trough has a complex structure rather than other troughs in Sirt basin. For instance, the trough was relatively inactive during the Palaeocene, but was reactivated again during the Eocene (Hallet, *et al.*, 1996). Internally the structure of the trough is complex. Gravity and magnetic data suggest the presence of a deep ridge within the trough, centered on the A1-119 well and extending in a north-northwest direction (Calbick, 1964, Maguireand Brow, 1981).
The Upper Sabil Formation defined in wells available in the study area is separated from the Lower Sabil by the distinctive Sheterat Formation. In the type well the formation comprises about 790 ft of chalky limestone and hard crystalline dolomite, with minor anhydrite.
Dolomite and anhydrite become more abundant in the area east of the Amal field (Hallet, *et al.*, 1996. The formation represents deposition on a shallow, sometimes restricted shelf, but

further north, in the Ajdabiya Trough, it passes into a deeperwater facies. The southern end of the Ajdabiya Trough represents a large re-entrant in the outline of the Zaltan/Sabil shelf, largely filled with shales. However, stratigraphy setting for a group of pinnacle reefs formed of Upper Sabil reefal carbonates totally encased in shales. These are the famous Intisar reefs which host large volumes of oil in excellent quality reservoirs. It is also oil bearing at As Sahabi and Al Mheirigah in the same area. Well and seismic data show that the Upper Sabil Shelf has an abrupt rimmed margin around the Ajdabiya re-entrant which is about 25 km long by 20 km wide in which the Upper Sabil carbonates are replaced by shale(Hallet, *et al.*, 1996).

The pinnacle reefs developed within the re-entrant, starting as foraminiferal mounds on the surface of the Sheterat Formation and developing into coral reefs later to be buried by shale. Eight or nine pinnacle reefs have been found, most of which are oil bearing. The Intisar A and D reefs are over 1,000 ft thick and 5–6 km in diameter and contain original oil in place of well over a billion barrels each. Porosity in the coral reef facies is 20–25%. The coral reef unit, which forms a cap to the pinnacle, contains coral colonies in growth position which are surrounded by a micritic matrix. The original aragonite of the corals has been removed by solution leaving extensive mouldic porosity. A regional stratigraphic cross sectionA-B in the central part of Sirt basin shows in figure 2.0, which illustrated a thick Palaeocene sequence in the Ajdabiya trough.

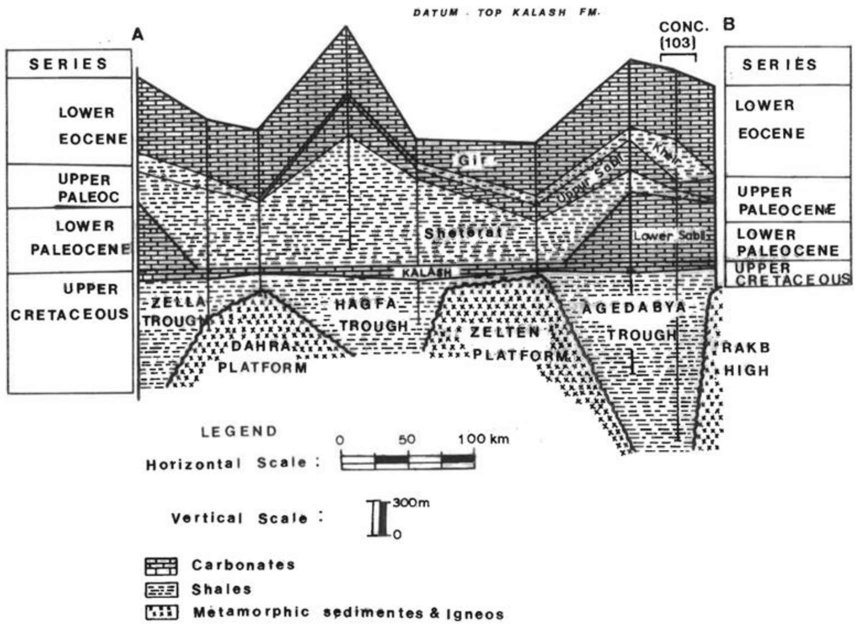

Fig. 2.0: Stratigraphic cross-section A-B in the Sirt basin, located in fig. 1.0, datum on top of upper creaceous (Kalash). Lower palaeocene carbonate wedge out over troughs, independent of location of earlier highs (after Brady, et al., 1980).

Seismic characteristics of carbonate buildups

The interpreted seismic sections across the reef in the study area recognized a type of pinnacle reef**,** which build vertically and extended for a few kilometers (≈ 5 km) laterally. There are variations in seismic attributes caused by geological changes, which directly show the shape of the reef as illustrated in the 2-D seismic section U14-103 (fig. 3.0).

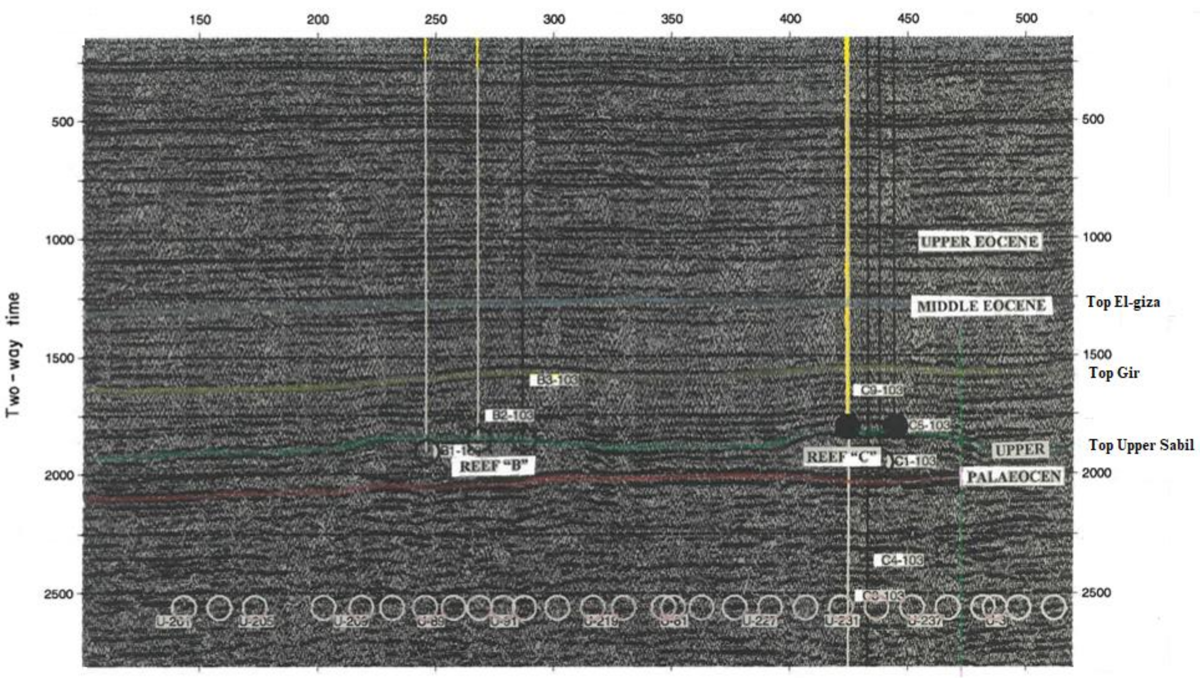

Fig. 3.0: 2-D seismic section (U4-103) cross the two reefs B and C, showing good evidence for them; (1) Convex shape at the reef top, (2) overlying drape, (3) Break up of reflections at reef edge, (4) Little or no continuity through reef mass, (5) velocity sag under the reef due to interval velocity of the reef being lower than that of the surrounding.

The reef identification and proper delineation was based on variations in the strata associated with the buildups. The seismic characteristics of the buildups and adjacent strata differentiate by depositional topography, facies changes and interval velocity density contrasts.

A reflection outlining tops and sides of buildup, drape in overlying beds, and negative velocity anomaly (off-reef micritic limestones and shales have higher interval velocity than porous, lightly cemented, Tertiary reef carbonate). Overall aspect of this pattern is so-called "eye effect". A pronounced velocity contrast commonly exists between the buildup and adjacent strata, resulting in differences in seismic travel time through these strata. Reflections below a buildup with slower interval velocities than those of the surrounding strata will be "pulled down" below the buildup (fig. 4.0).

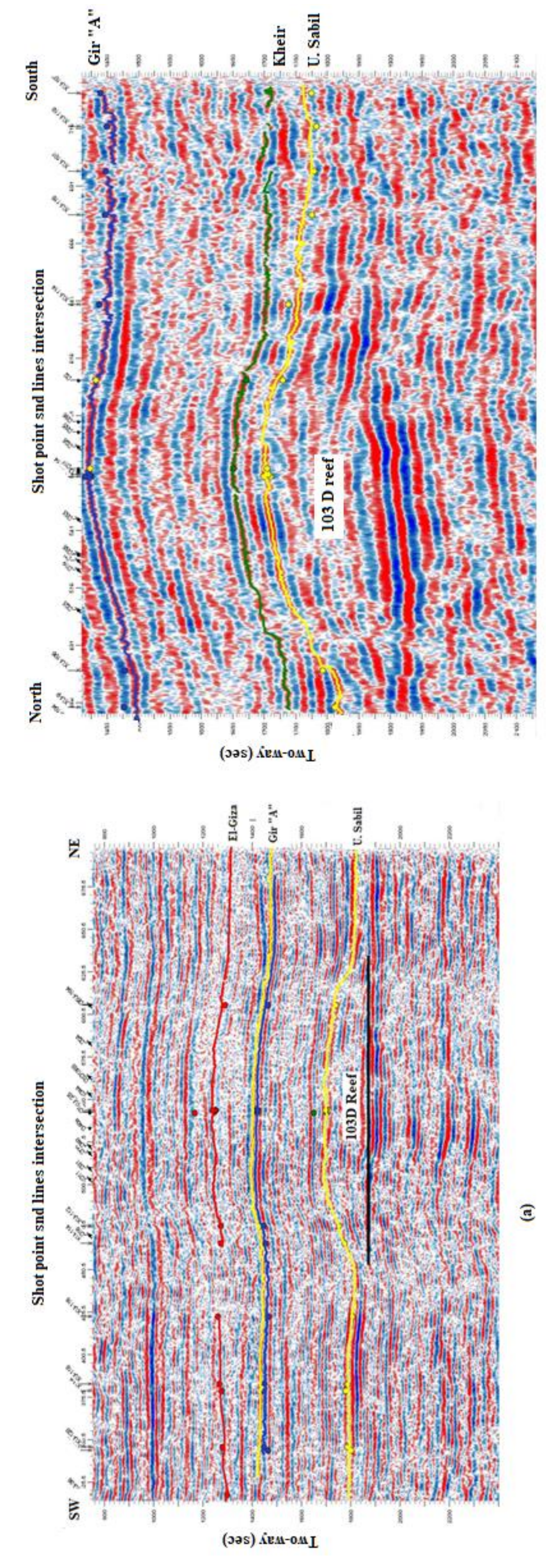

Fig 4.0: This high quality seismic line shows anomaly interpreted as pinnacle reef, (a) NE-SW 3-D seismic section, (b) N-S seismic section shows the same area of fig. (a) with large scale, both seismic sections cross the 103 D reef

Such seismic attributes are the reflections from the top andflanks of the reef, the seismic amplitude and continuity which depends on differences in characteristics of bedding continuity, density and velocity between strata.

Seismic facies analysis describes and interpret the seismic reflection parameters variations caused by geological changes in the reef and adjacent sediment package, the parameters are configuration continuity, amplitude, frequency and interval velocity.
Figure 5.0 shows the seismic interpretation in section U-51, where the seismic horizons tied with well stratigraphy (D1-103) located near the previous seismic line. In this seismic section some stratigraphic tops in the boreholes have no seismic response at the well location as in top Oligocene, which may due to similar acoustic impedance with the underneath sequence.

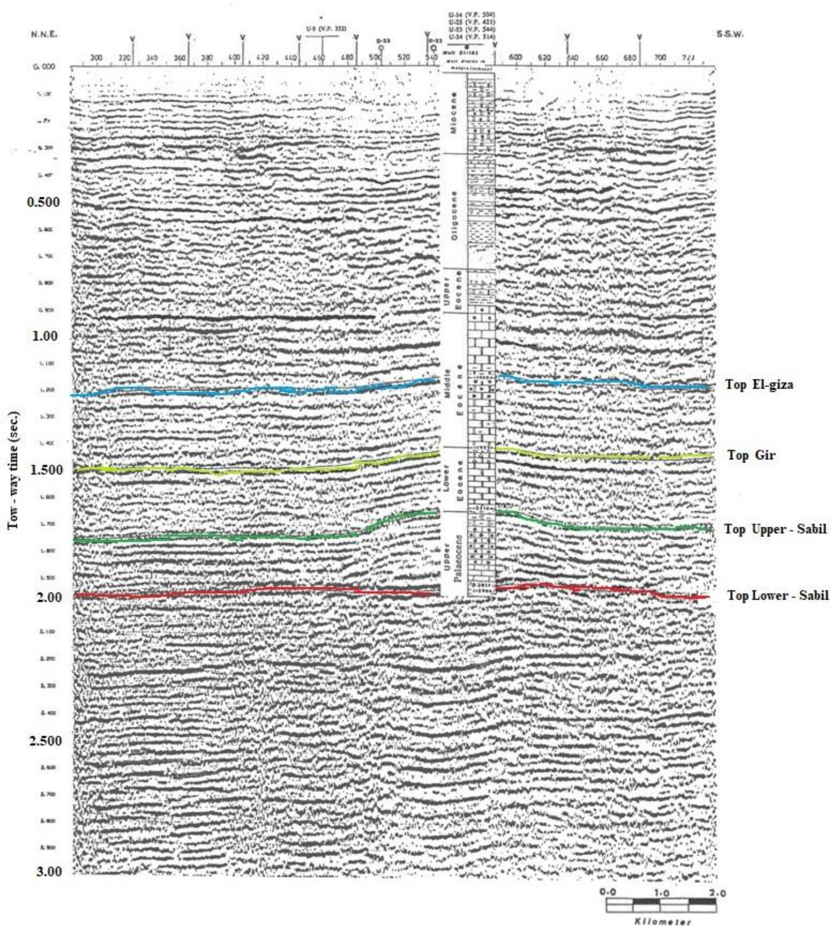

Fig. 5: Correlation of seismic horizons (line U51-103) and well stratigraphy (D1-103).

Synthetic seismogram

Figures 6 (a), (b), and (c) show synthetic seismograms for wells N2, E1, and L1-103 respectively. The synthetic seismograms were based on sonic velocity changes only, whereas the density logs are not available in these wells. The procedures for the construction a synthetic seismogram well known; where the reflection coefficients are calculated from acoustic impedance changes, then the reflectivity series is convolved with a Ricker wavelet with a peak frequency of 30 HZ. A synthetic trace which has been get it is a fundamental aid in identifying and predicting how stratigraphic variations may affect a seismic record. Stratigraphic tops may have no seismic response at the well location. Moreover, the stratigraphic tops based on palaeontology could also be wrong, as generally the palaeontological resolution is much poor than that of seismic, or may not corresponding to a significant acoustic impedance change (Badley, 1989). According to previous statement top

Gialo (Middle Eocene) horizon provides an excellent regional marker, where it was picked at a level where there is no significant acoustic contrast. Its depth differences acoustic impedance variation occurs in well N2-103 at a level 110 m shallower than the level of the acoustic contrast (Fig. 6 a).

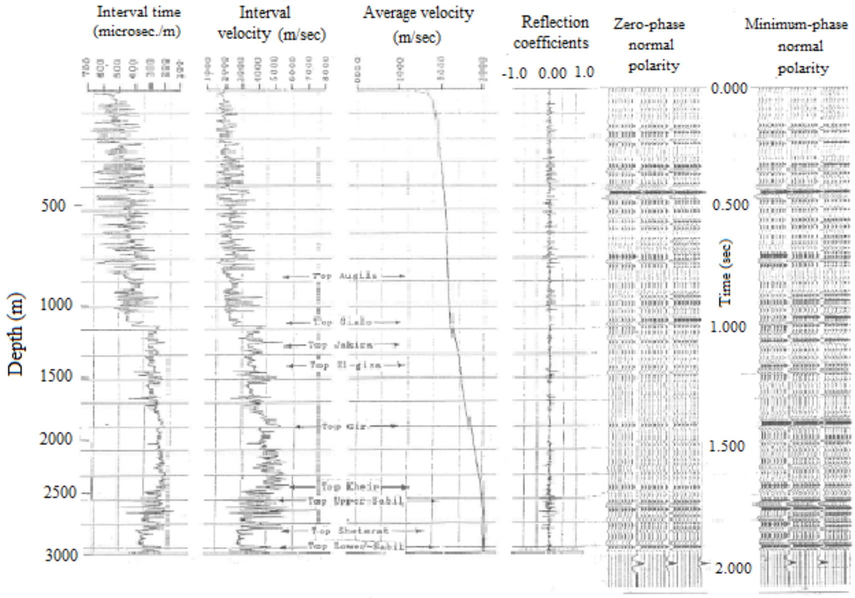

Fig. 6(a): Synthetic seismogram display derived from acoustic log in well N2-103

In well E1-103 about the same interface is 90 m lower than the level of the acoustic contrast (Fig. 6 b).

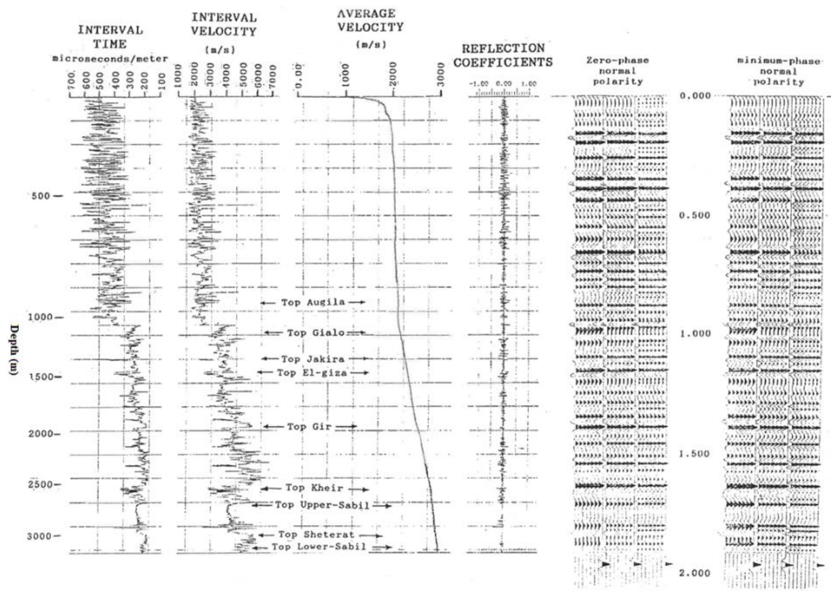

Fig. 6.0 (b): Syntheyic seismogram display derived from acoustic log in well E2-103

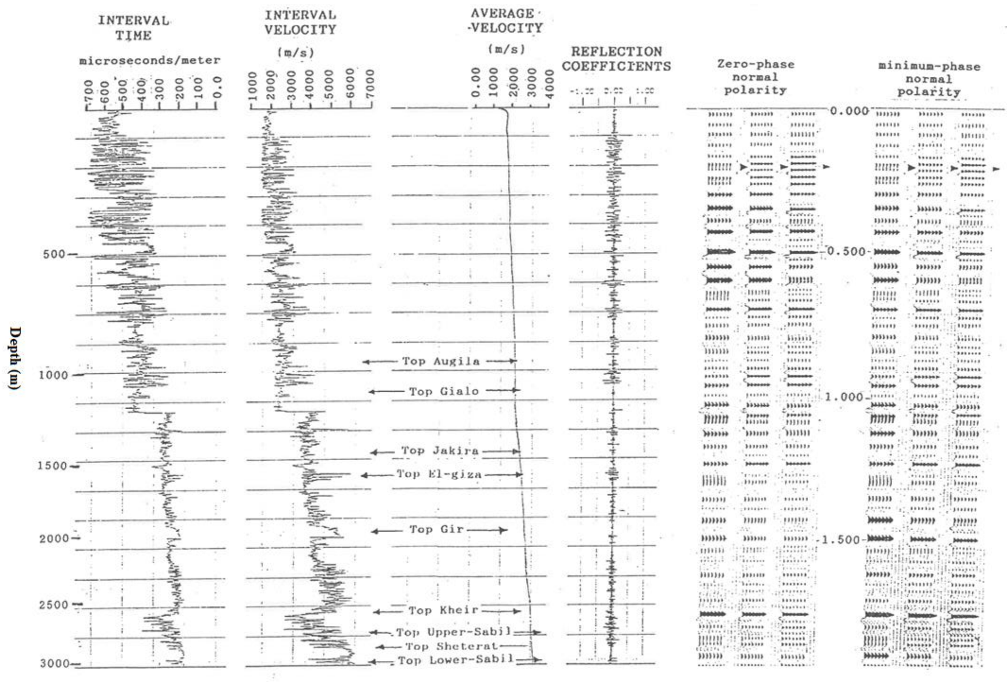

Fig. 6.0 (c) Synthetic seismogram display derived from acoustic log in well L1-103

The explanation for the differences in the picking of Gialo formation above and below the level of the acoustic impedance, that the well log stratigraphy is dominantly lithostratigrahic (a rising mainly from the correlation of wireline logs with subordinate palaeontology control), whereas the seismic stratigraphy is both chronostratigraphic and lithostratigrahic. This can lead to significant differences in the placing of sequence boundaries between well and seismic. Wells are also often drilled at stratigraphically anomalous locations.

Linking well geology to the seismic reflections

The seismic interpretation started by making a link between borehole measurements and the seismic sections. The velocity survey is only the first link to put data on the same scale. From the time-depth curve one can assign two-way reflection times to the principal geological interfaces in the well and identify reflections on the seismic section. Results of well survey in well U1-103 are shown in figure 7.0.

Once the common scale is obtained, it is necessary to make a direct comparison between borehole logs and the seismic trace along the well. The tying in the well data is to calculate the two-way seismic time to the reflecting boundaries. The tying of the well and seismic data is an essential step in interpretation. The process begins with an analysis of the data collected in the well.

Comparing the two-way times observed in well (E1-103) with the seismic section (U1-38) close to the well. Table 1.0 reveals seismic time differences up to 59 msec in some stratigraphic levels.

Table 1.0: Two-way time in well E1-103 and in seismic section U-38 with mis-ties

Formations	Depth (m)	Tow-way time (msec.) (well)	Two-way time (msec.) (seismic)	Mise-tie (msec.)
Au-Gila	-956	878	845	∓ 33
Gialo	-1123	1000	985	∓ 15
Jakira	-1363	1100	1100	0
El-Giza	-1484	1158	1190	∓ 32
Gir	-1958	1390	1400	∓ 10
Kheir	-2534	1646	1705	∓ 59
U.-Sabil	-2645	1707	1730	∓ 23
Sheterat	-3005	1865	1860	∓ 5
L. - Sabil	-3020	1902	1910	∓ 8

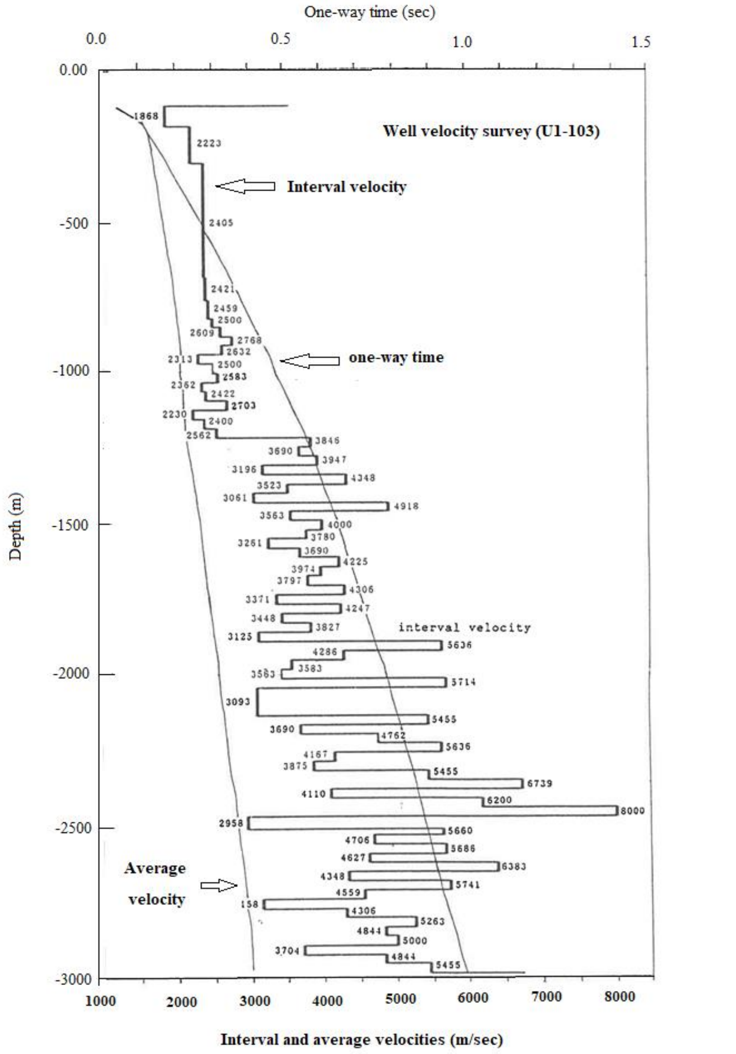

Fig. 7.0: Interpretation of the results: relations of time with depth, average velocity with time and interval velocity with depth (U1-103), sea level datum

Figure 8 (a) shows that well to seismic tie matches reasonably closely, particularly at the Upper Eocene (top jakira formation), Lower Eocene (top Gir) and Upper Palaeocene (top Sheterat).

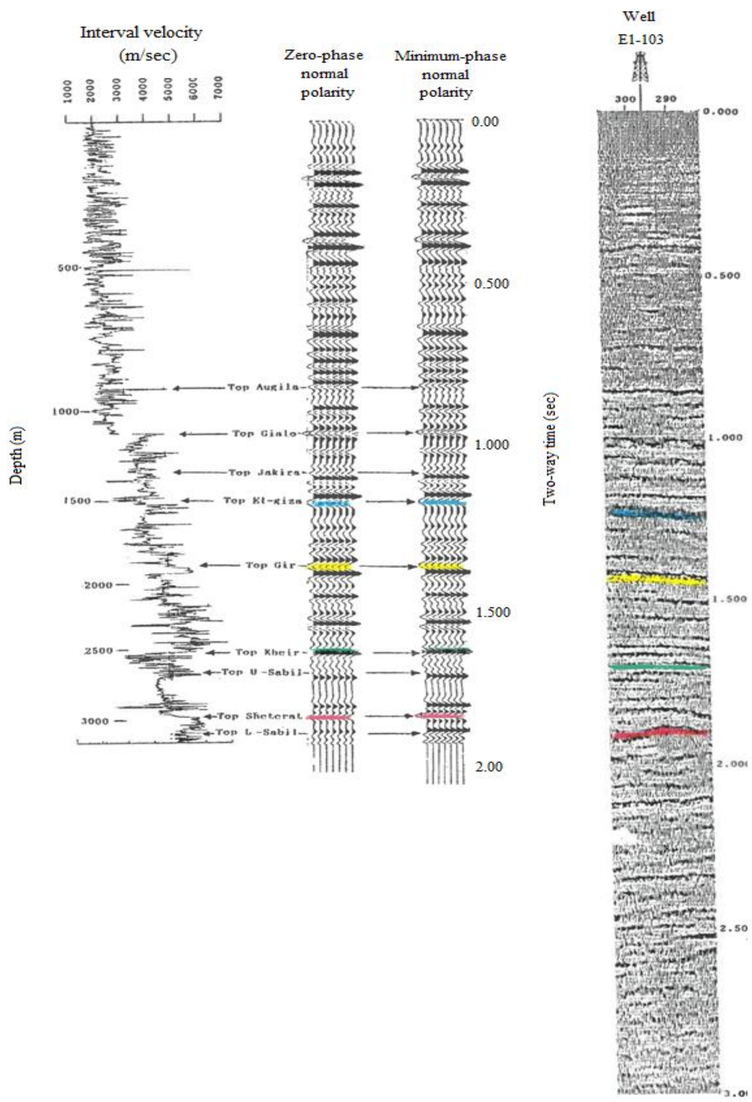

Fig. 8 (a): Comparison of synthetic (well E1-103) and a part seismic section (U38-103)

Comparing the two-way times observed in well (L1-103) with the seismic section (U69) close to the well. Table 2.0 reveals seismic time differences up to 33 msec in some stratigraphic levels.

Table 2.0: Two-way time in well L1-103 and in seismic section U-69 with mis-ties

Formations	Depth (m)	Tow-way time (msec.) (well)	Two-way time (msec.) (seismic)	Mise-tie (msec.)
Au-Gila	-874	732	710	∓ 13
Gialo	-1088	978	970	∓ 8
Jakira	-1287	1074	1060	∓ 14
El-Giza	-1440	1189	1170	∓ 19
Gir	-1891	1405	1390	∓ 15
Kheir	-2491	1663	1630	∓ 33
U.-Sabil	-2583	1708	1700	∓ 8
Sheterat	-3833	1845	1830	∓ 15
L. – Sabil	-3989	1892	1865	∓ 27

Figure 8 (b) shows the match of the zero phase (symmetric wavelet with maximum amplitude at the acoustic impedance (AI) boundary), and the minimum phase (maximum amplitude in first peak or trough of the wavelet which starts at the acoustic impedance (AI) boundary) synthetic seismograms with the seismic sections. The minimum phase wavelet reflections have high amplitude in most seismic events. A good well tie shows a good correlation of shape and amplitude for peaks and troughs between the synthetic and seismic section.

The mis-tie originates due to various reasons. Firstly, even for a perfectly vertical well the seismic trace does not follow a purely vertical path, especially if the sedimentary series has contrasts and dips. Secondly, any deviation from the ideal horizontal, parallel layer structure introduces distortion in the timing multiples and the trace treatment in general. Other systematic mis-ties can arise because of phase distortion, wavelet interference, or incorrect static correction. Finally, the previous seismic sections are not migrated. It is well known that most stratigraphic evidence of onlap, reefs and so on, involves angularity reflections most be migrated in order to be properly positioned.

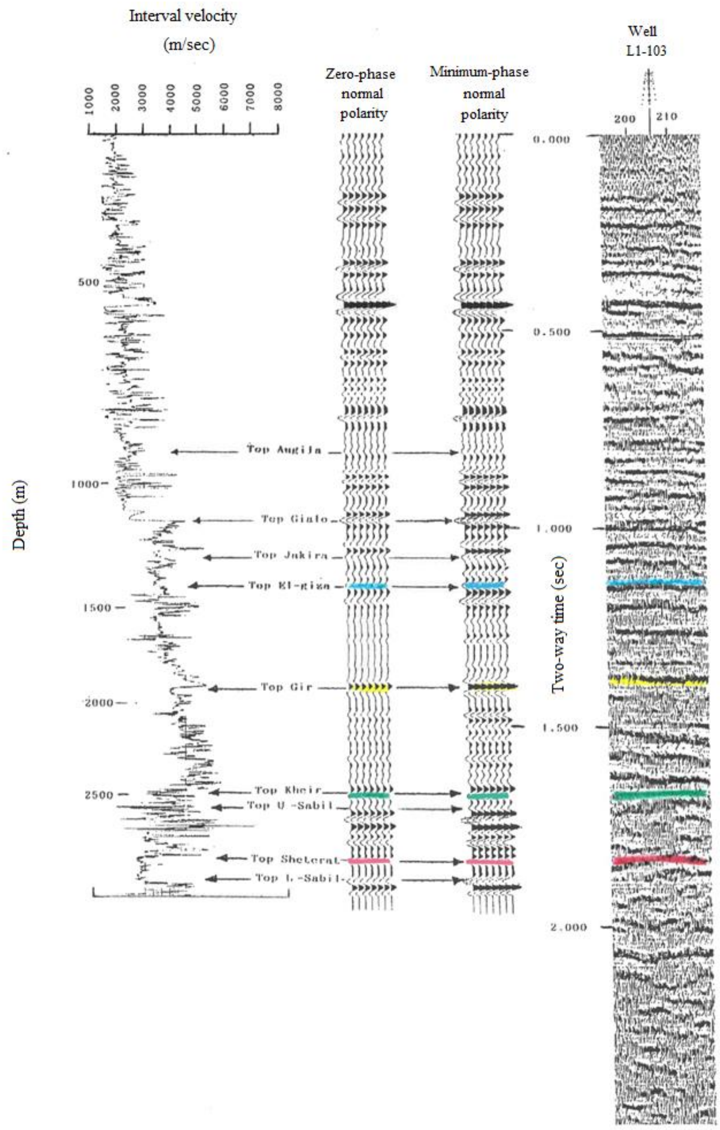

Fig. 8(b): Comparison of synthetic (well L1-103) and a part from seismic section (Line 69)

Seismic interpretation and mapping

A unique opportunity to control the interpretation of data is offered based on wells with total depth over 3000 m with lithologic data available for most of them. The distribution of two dimension (2-D) seismic survey and wells in the area of study shown in figure 9.0. Reflecting horizons are identified on the seismic sections starting from well U1-103, The four seismic reflectors can be followed on line U-66 and its intersection with other seismic lines. The objective of tying lines to trace the lateral continuity of each selected even. In this way the interpretation can gradually be extended from the well to eventually cover the total grid of seismic survey.

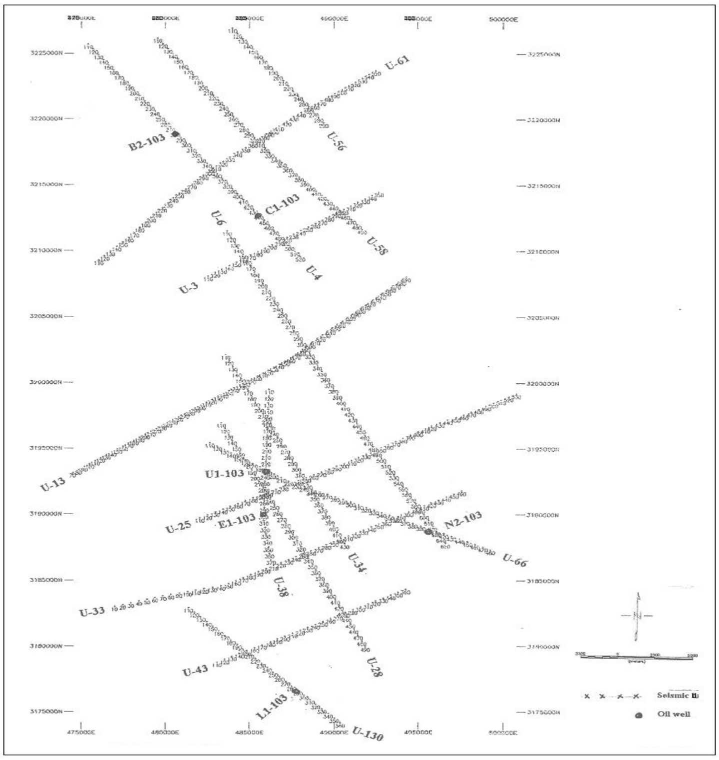

Fig. 9: Base map of seismic lines and wells in the study area

Identification of seismic reflectors

The event identification procedures adopted, together with the selection of seismic marker most suited to reveal the stratigraphic detail of the study area. The criteria governing seismic event identification are multifold, based upon the well control of the
seismic data, and the seismic boundary conditions according to the principles of seismic sequence stratigraphy.

The velocity log available in well N2-103 overlain on the seismic section U-66 (fig. 10). The marked velocity breaks occur clearly in the following tops at the Palaeocene package starting from the old; (i) Sheterat, (ii) Upper-Sabil, (iii) Kheir, (iv) Gir, (v) El-Giza, and (vi) Gialo. Each of previous tops produces a strong reflector over a large area with good continuity, which can identify in the seismic sections, particularly top Gir and Gialo as a result of velocity and density contrast. Event identification made on the basis of character and arrival time, the two-way time in the intersections were picked carefully with the reasonable mis-tie.

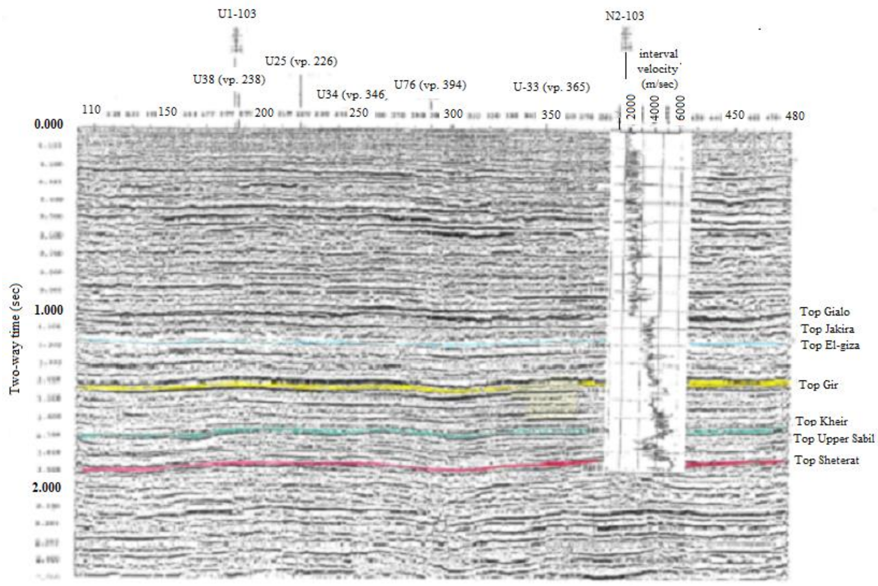

Fig. 10: Seismic section U66-103 shows the crucial importance of the link between well N2-103 and seismic data. interval velocity displayed in the sonic log of the well

The interpreted horizons have been tied with well top formation by using velocity log. The strong and obvious reflecting interface such as top Gialo (Middle Eocene) appears very clear in the well log, this boundary can be correlated with the most obvious reflector on the seismic sections. Using this reflector as a reference during the interpretation, other reflectors can be tied. Four seismic horizons have been chosen for mapping, top Sheterat, Kheir, Gir, and El-giza.

Top Sheterat

This is the deepest sequence interpreted in the area, it is a fairly low frequency event clearly defined by a trough, it has a high amplitude with a negative reflection coefficient due to change of depositional sequence from carbonate (Lower Sabil) to shale (Sheterat) and high continuity over large area.The Sheterat Formation separates the Lower from Upper Sabil carbonates. Where the Sheterat Formation is absent it is impossible to separate these two units. The Sheterat Formation is equivalent to the Khalifah shales of the western Sirt Basin, and represents a short-lived flooding event.

Top Upper -Sabil

The top Upper-Sabil was the deepest horizon to be interpreted. It is a fairly low frequency event clearly defined by a trough, and was carried across the survey with good certainty. The Upper-Sabil reflection has a high amplitude with a positive reflection coefficient, and high continuity over large area in the field, that is due to the change of the depositional sequence from shale (Kheir) to carbonate (Upper-Sabil) under low energy conditions. This event shows the pull-down beneath the reef, due to low velocity.

Top Kheir

Top Kheir marker is the closest continuous event to the top of the reefs in the area. It is represented as a comparatively medium / high frequency peak, with good continuity and medium amplitude.

The Khayir Formation has a wide distribution in the Sirt Basin. It averages 200 ft in thickness in the south-eastern Sirt Basin, and 300 ft in the Ajdabiya Trough, but is absent on the Sabil carbonate shelf due to subsequent erosion. The Khayir Formation represents an effective regional seal for the underlying carbonates within the Harash, Zaltan and Upper Sabil Formations over much of the basin.

Top Gir

This horizon marks the top of Lower Eocene. It picked as a signal trough immediately above the peak, it has low frequency which representative the geological tie. It shows good continuity and high to medium amplitude throughout the survey. The Gir horizon reflects drape over the reefs area. The drape appears clearly in B and C reefs due to differential compaction of strata in the buildup as shown in fig. 3.

Top El-giza

A conformable poorly defined trough represents it with good to fair continuity over the entire area and high to medium amplitude. The El-giza reflects drape over the reefs, the effect of drape generally dies out stratigraphically upwards.

Mapping reflecting horizons

Once seismic sections have been interpreted the next objective is to produce contour maps of two-way time for each horizon. The first stage in contouring is to record the two-way times to the picked horizons on the seismic sections and post these values on shot-point base map with suitable scale. Seismic interpretation is different from most other forms of geological mapping. It is because the grid consists of two-dimensional vertical sections. Areas without any data can only be sampled by shooting extra lines. Moreover, these maps can give us more information about facies changes with the same sequenced or para-sequence. Geologically, change in lithology, which may indicate changing in depositional environment, and from the Geophysical point view, change in velocity, density and other seismic characteristics such as amplitude and frequency.

Time contour maps

It is worthwhile producing time contour maps for previous picked horizons in the area of study. Two-way times are read off the seismic sections to the nearest 10 msec at uniform interval along seismic lines. The two-way time values are posted against the appropriate shot points along each seismic traverse. The posted values maps can then be contoured using suitable contour interval, it depends into sedimentary basin geological complexity. In the Sirt basin it was found 10 msec is a good contour interval. The contours show details of low and high relief areas and their direction. The contour maps established by using Geosoft.Maps constructed from seismic data represent structures in terms of two-way transit time.

Sheterat two-way time structure map

Time contour map with location of the seismic profiles. It shows smooth and simple contour (fig. 11) over the area, whereas time values increase gradually from south (1800 msec) towards north-northwest (2080 msec), indicating dipping to north.

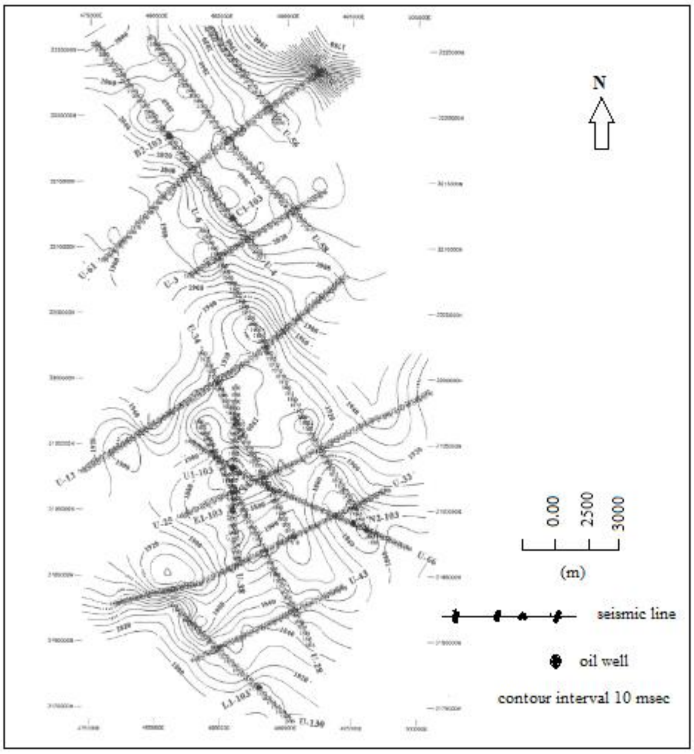

Fig. 11: Structure time contour map of top Sheterat (Upper Palaeocene)

Kheir two-way time structure map

The closest above the structure (fig. 12), it shows time contour of the top Kheir shale. Generally, it illustrates steep and dense with values ranges 1580 msec in the southern part to 1980 msec at north and northwest.

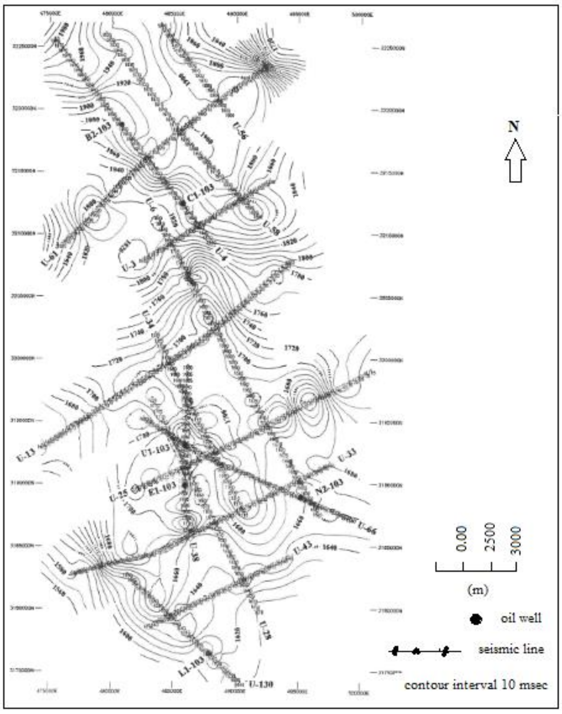

Fig. 12: Structure time contour map of top Kheir (Upper Palaeocene)

Gir two-way time structure map

It shows anomalies in south, center and north where their values 1360 msec, 1500 msec and 1620 msec respectively (fig. 13).

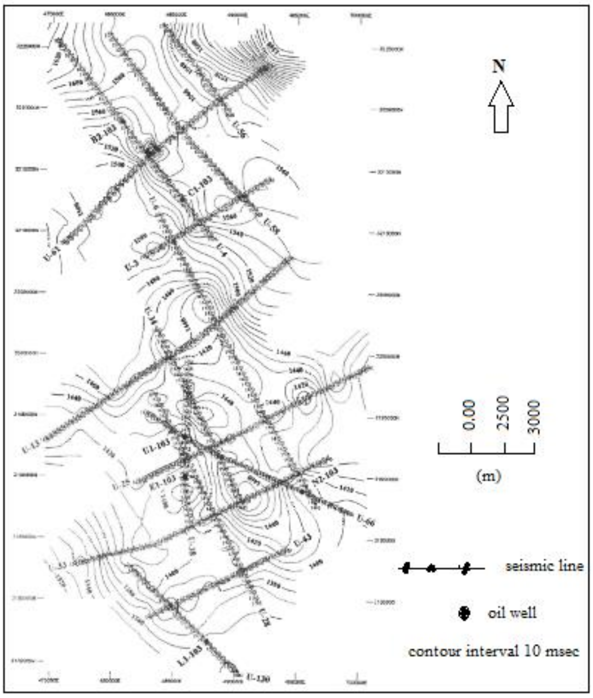

Fig. 13: Structure time contour map of top Gir (Lower Eocene)

El-giza two-way time structure map

The two-way time structure map of top El-giza reveals simple contours over the whole area (fig. 14). The contour values ranging from 1120 msec in southern part of the area into 1300 msec towards north and northwest.

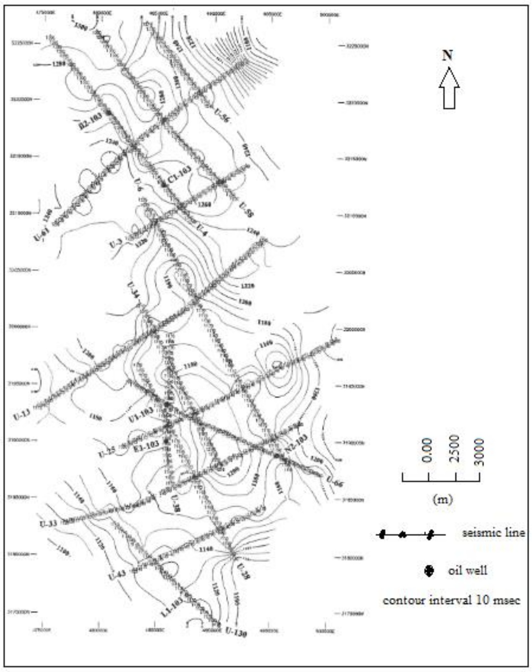

Fig. 14: Structure time contour map of top El-giza (Middle Eocene)

Conclusion

The major change in sonic log of top Gialo, Gir and Upper-Sabil sequences produce distinct events on the synthetic record for the whole available wells in the area, where in seismic sectionsGialolocated at 1.0 sec, at 1.4 sec for Gir and 1.7 for Upper-Sabil and showing a very strong reflection with good continuityand high amplitudesuggest major sequence boundaries. Generally, there is a good agreement between well and seismic with small mis-ties especially at the stratigraphic level mentioned above. The overlying sediments (Kheir) develop drape over the reef area about 7 msec, which shown in Gir and El-giza as well with low effect and less time. Part of this drape can be attributed to depositional thinning of the beds on the of the named sequences on the reef, but the greater part could be due to differential compaction. The automated contouring created some false features at the ends of seismic survey (e.g. line U61-103) in all two-time structure maps. A general dip towards the northeast have been noticed.

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