Petroleum Res. J. Vol. 21 (2008/2009); P. 67–80, 13 Figs.

Analysis of Fault Zone Characteristics Using Potential Field and Seismic Data, Al Hagfa Trough, Sirt Basin - Libya

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Abstract: In this study, gravity data has been used in conjunction with seismic data to map and model the structural and stratigraphic elements in and around Al Hagfa Trough of central Sirt Basin. 2D seismic data show that the erosion and truncation of pre-rift strata and the thinning and onlapping of syn-depositional sequences onto fault scarp suggest that the area has experienced rifting activities and erosion during basin evolution. The mapped fault zone attached to rifting is about 150 km long and is composed of three 45 – 50 km long normal planar segments. These segments are bounded on the east by an area of local gravity high (NW-SE orientation) which results from low contrast between the Palaeozoic basement and Mesozoic - Cenozoic rocks and defines the Zaltan Platform structural trend. The western boundaries are marked by both gravity highs and lows which includes Al Bayda Platform and Al Hagfa Trough. The gravity minima are associated to longitudinal synclines or growth nuclei best explained by recognizing that it is a thick sequence of predominantly sedimentary wedges, including syn and post-sediments. Gravity modeling demonstrates the nature and structure of the mapped troughs and platforms, for a particular fault segments. Tilted segments can be observed also on the Bouguer and horizontal gradient maps. The southern portion of the fault block has a nearly N-S trend due to tilting. The mode of extension has important consequences for the Cretaceous hydrocarbon plays associated with the rifted province of Al Hagfa Trough. A breached relay ramp as evidenced from seismic and gravity data probably has a great influence on the hydrocarbon migration and entrapment in the study area.

INTRODUCTION

Geophysical methods (gravity and seismic) are used to provide control on the structure and stratigraphy of the subsurface related to faulting along a major fault zone separating the Zaltan Platform and Al Hagfa Trough in the central Sirt Basin (Fig 1). The area under study comprises large scale fault systems combined with broad syn-rift sequences evolved during time of basin evolution. Several significant features that reflects the nature of the subsurface are: (1) the anomalous low and high gradient in the area between the Zaltan Platform and Al Hagfa Trough, (2) the anomalous orientation of the anticlines and synclines like structures with respect to fault system evolution. The timing of rifting episodes in the Sirt Basin is thought to have commenced in Triassic, intensified in the Jurassic - Lower Cretaceous and terminated in Upper Cretaceous, (Busrewil et al., 2008). Overburden was largely deposited during the post-rift sedimentation stage (Oligocene and younger). Pre-rift and early syn-rift deposition (Fig. 2) was largely clastic whereas later syn-rift deposition was dominated by carbonate deposition. The deepest troughs in the basin, such as Ajdabiya Trough, (Fig. 1), have more than 7,000m of sediments, of which 5,500m are of Tertiary age (Hallett and El Ghoul 1996). Eighty percent of the drilling programmed in the province have been on platform horst areas at depths less than 3,000m. The Precambrian basement depth within the Sirt Basin approaches 5,000m within the southern part of the Ajdabiya Trough and is generally around 2,000m in the platform areas. The basement is generally deeper in the southern part of the Sirt Basin than in the northern part, and it is deeper in the eastern part than in the western part.

Al Hagfa Trough (Fig. 1) is characterized by high subsidence rates during the Late-Maastrichian and a slow subsidence rate during the Palaeocene (Ahlbrandt, 2001). The Zaltan Platform with the same time is characterized by continuous subsidence during the Late-Maastrichtian and Palaeocene (Meer and Cloetingh, 1993).

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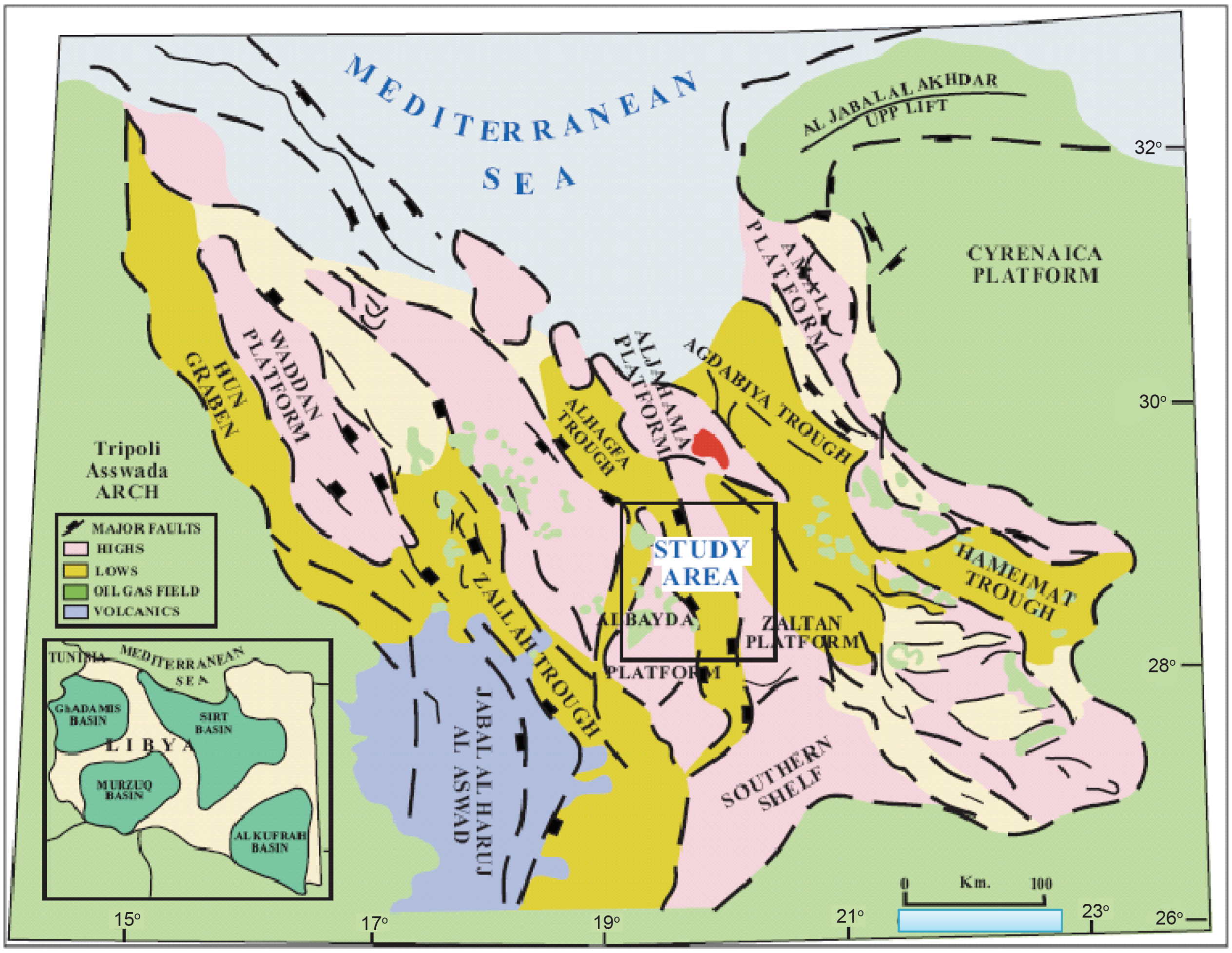

Fig. 1. Sirt Basin tectonic elements and location of the study area, modified form Lasmo Grand - Magreb map (1998).

The differences in both magnitude and direction (uplift or subsidence) of movement of all the basement blocks, with respect to each other, indicate syn-sedimentary normal faulting typical during rifting events. These rifting phases are followed by a period characterized by decelerating subsidence rates during the Eocene to Early Miocene. During the Eocene, deviations from this subsidence pattern can be observed, and affect the analyzed basement blocks in the Sirt Basin. The subsidence rates decelerate to very low levels during the Oligocene – Early Miocene (Meer, and Cloetingh, 1993). Previous geophysical publications focusing on fault zone evolution in the study area are very limited, although several regional studies are available (Andrew, 1994). Gravity and magnetic maps of the Sirt Basin region have demonstrated the value of these data for mapping general basin structures, basement morphology (Libyan Gravity Compilation Project LPI 2002).

Previous seismic studies have focused on the local near-surface features such as thickness of surficial sediments and basin structures required for hydrocarbon exploration. It is aimed through this study to outline the general context of the study area by using integrated geophysical data.

GEOPHYSICAL DATA AND METHODOLOGY

Complete Bouguer Gravity Map

The gravity data used in this investigation (Fig. 3) was taken from the Libyan Petroleum Institute (LPI) data base. The LPI staff compiled and processed data from a number of local surveys. The processing included projecting the data onto a 2 km regular grid using a minimum curvature interpolation technique, and a Bouguer correction using a density of 2.67 g/cm3. The residual Bouguer gravity map of the study area (Fig. 4) is produced and mapped according to a standard colour code, representing the Bouguer gravity values). Red colours represent regions of high

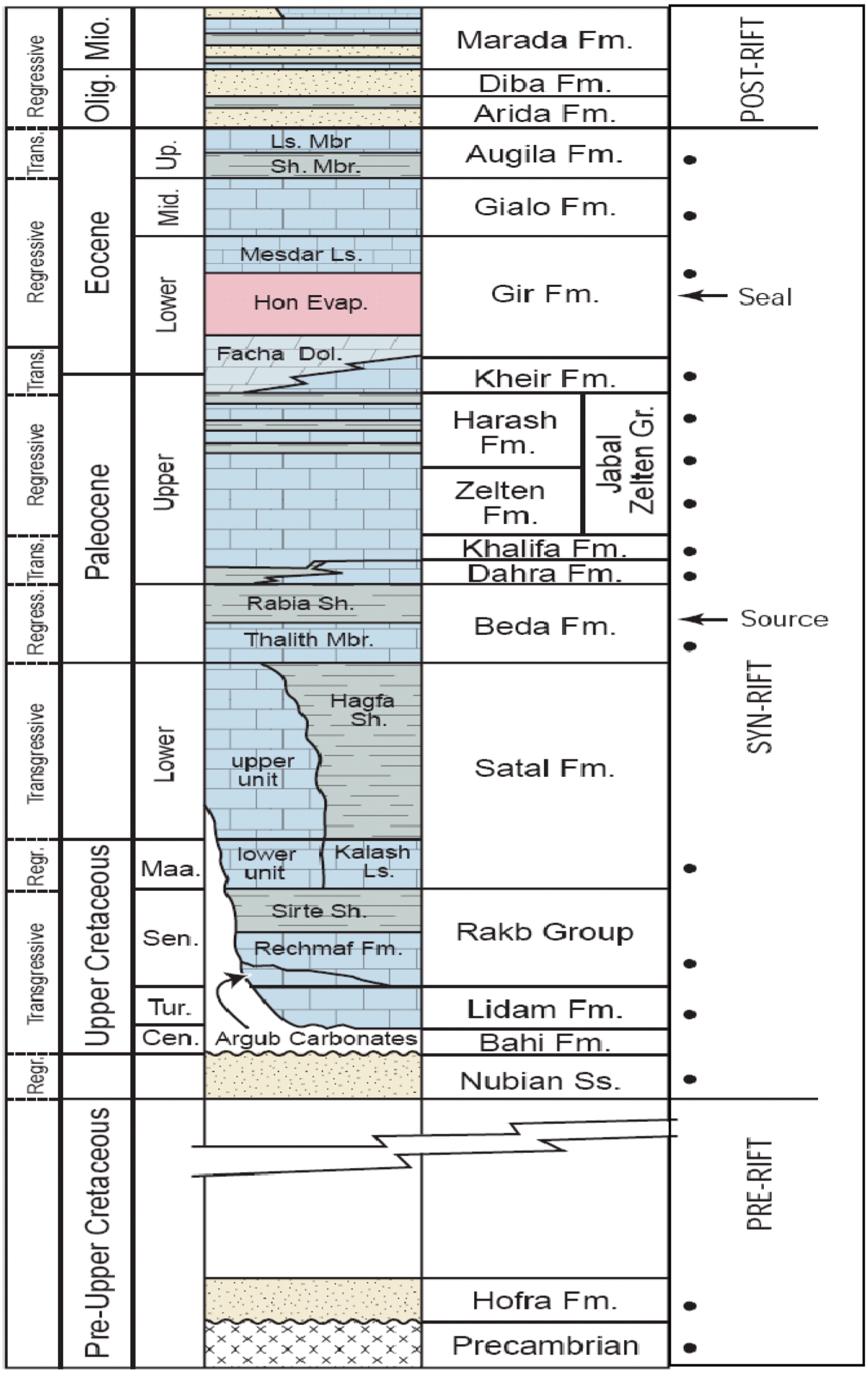

Fig. 2. Stratigraphic section in central Sirt Basin (after Ahlbrandt, 2001).

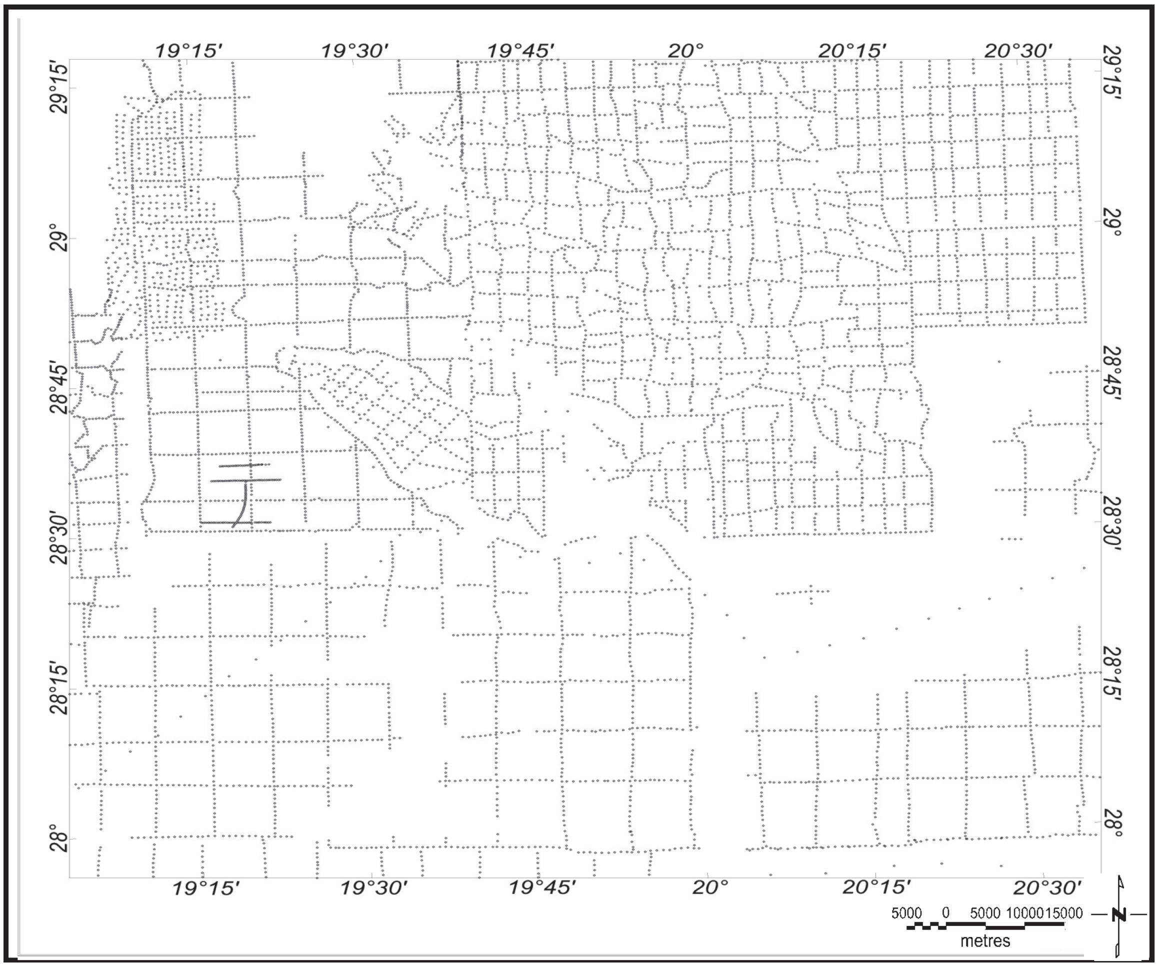

Fig. 3. Gravity station coverage over the study area.

relative density and blue colours represent regions of low relative density.

To remove the regional trend caused by the mantle- crust interference and to bring out local details in the gravity field as displayed in Figure 4, the original Bouguer gravity data (not displayed) were input to a spatial filter (the two-order polynomial filter), designed to attenuate the component of the gravity field. The resulting data are shown in (Fig. 4) with geologic contacts superimposed.

The filtered data (Fig. 4) show the characteristic Bouguer gravity high (red) associated with the Zaltan and Al Bayda platforms, the (blue) associated with sedimentary sub-basin structures representing Al Hagfa and Al Wadayat Troughs, and the intermediate values (yellow) probably associated with signatures of remnant Palaeozoic and Mesozoic rocks. The gravity signature varies considerably along the axial trend of the mapped sub-basins. In the western portion of the study area (Al Hagfa Trough) a large gravity low is observed. This implies a large density contrast between the basin fill and the basement. A filtered total horizontal gradient of the residual Bouguer gravity (Fig. 5) shows clearly the structures and the contacts superimposed.

Al Hagfa Trough is bounded by the major fault as shown in the Bouguer and gradient maps (Red colours). This fault is segmented along the strike and comprised of three fault segments. This suggests that Al Hagfa Trough may contains variable basin fill sequences, but a portion of this low gravity response may be attributable to the regional effect of the denser crust in the region.

In addition to the gravity imaging, 2D forward models demonstrating the identified features were constructed from the residual gravity data. Time unit densities were assumed for these models based on previous studies.

Seismic Data

Three migrated seismic lines from block NC 144 and concession 71 were used. The lines extended

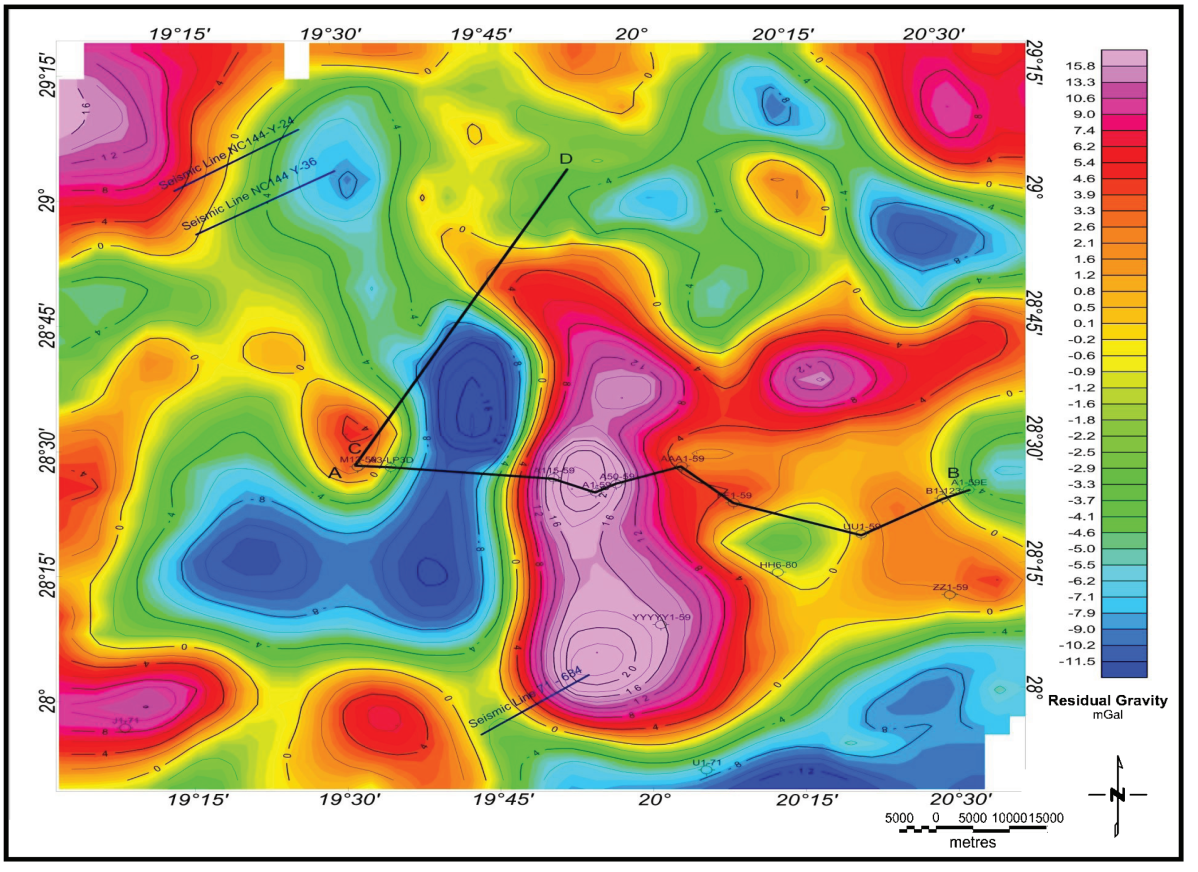

Fig. 4. Bouguer gravity map of the study area with locations of gravity profiles and seismic sections.

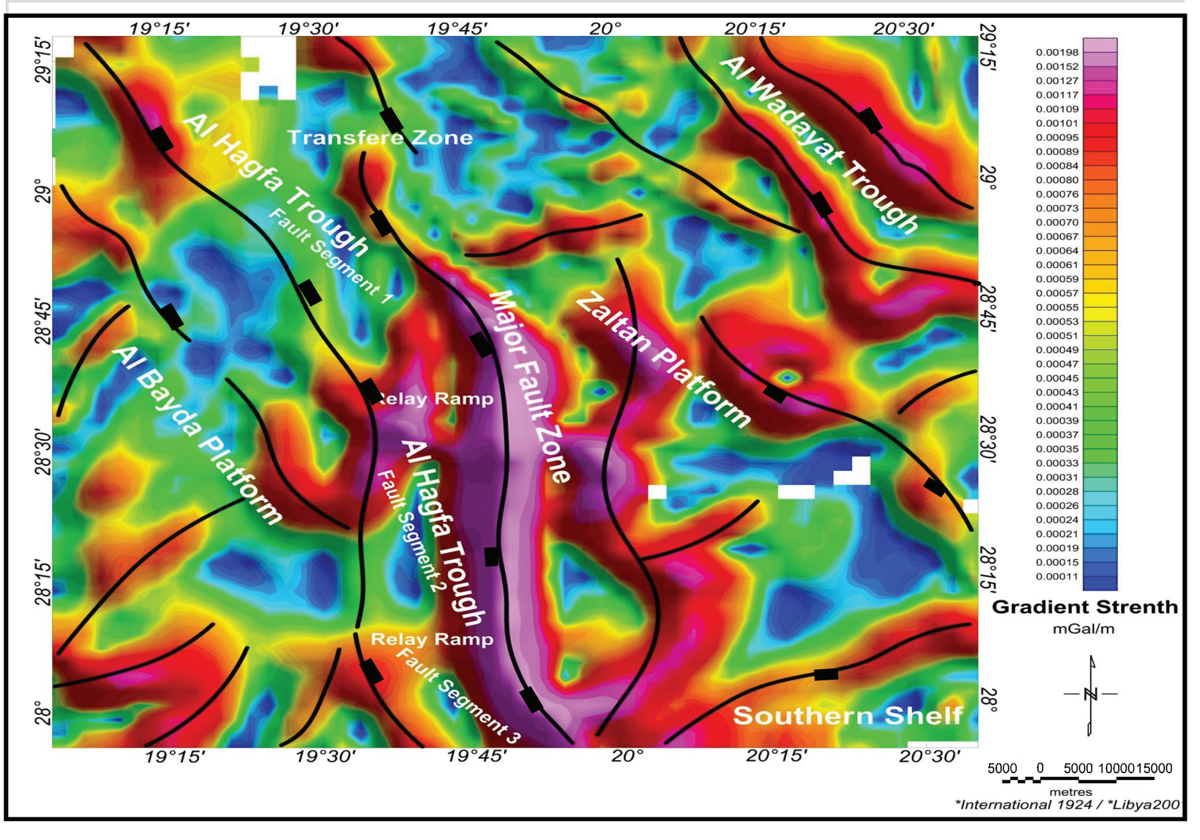

Fig. 5. Total horizontal gradient map of the Bouguer anomaly showing location of fault zones and boundaries of troughs and platforms.

NE – SW and some of them crosses the mapped fault zone.

INTERPRETATION CONFIDENCE

The residual Bouguer gravity anomaly map of the study area (Fig. 4) shows various trends and structures. Negative anomalies are found to be consistent with sub-basins whereas positive anomalies reflect structural highs. The complex pattern of the gravity anomalies can be used to define three main structural domains, comprising from east to west: (1) Zaltan Platform domain, with a NW–SE positive anomaly (2) Al Hagfa Trough domain, characterized by a gravity low and bounded from the east by a major fault zone trending NW – SE direction, and (3) Al Bayda Platform domain, marked by a broad NW–SE trending positive anomaly (Fig. 5). The three domains coincide with high and low structures characterized by a gradual displacement variations along-strike. Approximate limits are proposed to better define the boundaries of the three zones or domains.

The Al Hagfa Trough domain is better defined from the east with the major fault zone of about 150 km long, and combined of three fault segments (normal and planar). Each fault segment has a length of about 45-50km. The segments are bounded from the east by an area of regional gravity high (NW-SE orientation) which results from low contrast between Palaeozoic basement and Mesozoic - Cenozoic sedimentary sequences and defines the Zaltan Platform structural trend. The western boundaries are marked by both gravity highs and lows, and comprise the Al Bayda Platform structural domain. Segments tilting can be observed in the horizontal gradient map. The southern portion has a nearly N-S trend due to tilting. The change in fault orientation along strike gives the fault zone a zigzag pattern in plan view (Figs. 5 and 6 A - D).

Rollover structures within longitudinal synclines may be formed as a result of block tilting and/or probably due to radial propagation during fault growth. There are a number of NW-SE trending

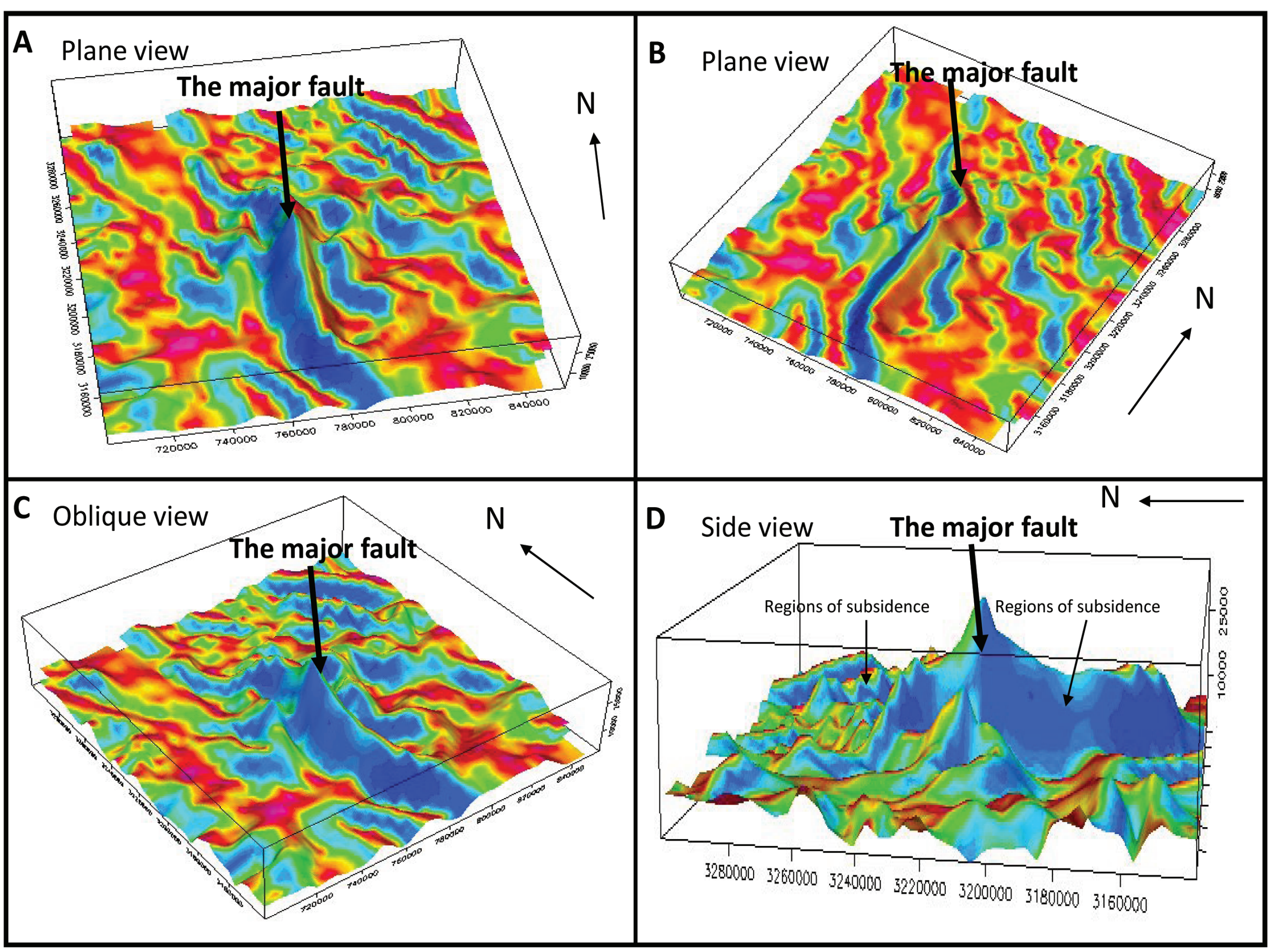

Fig. 6. 3D perspectives of the horizontal gradient surface depicting the major fault zone and structural highs (warm colours) and adjoining regions of subsidence such as longitudinal synclines (blue colours).

faults separated into sub-populations of probably synthetic and antithetic faults of variable arrays that can be observed in the residual anomaly and the horizontal gradient maps (Figs. 4 and 5). Other E-W trends can be observed in the maps which terminate against the major fault at relay zones and crossing the foot-wall and the hanging-wall in some places.

They were formed during interactions between different fault segments during segment linkage processes. In other cases the gravity minima are associated with longitudinal synclines or growth nucleus which related to fault evolution and rifting, best explained by recognizing that they are thick sequences of dominantly sedimentary rocks, including syn and post sediments.

Syn and post rift structures can be observed from seismic section (Fig. 7). The character of the seismic reflections shows evidences of rift patterns. It has been concluded that the attached graben to the bounding fault shows a model of hanging-wall with characteristics of different stacking patterns which in general reflect the nature of the rift features along the fault strike. It is suggested that, within and around the defined fault block, the uplifted area or crest is eroded and the eroded materials were transported and deposited on both sides of the crest forming initial syn-rift sediment wedges, with the greatest thickness at the immediate hanging-wall of the fault. The syn-rift and post-rift sediments of the hanging-wall of the large fault typically show monoclinal structures dipping into Al Hagfa Trough. These structures are interpreted to have been generated either by fault propagation during fault growth processes or through compaction of the sediments over the fault step in the basement.

Fault displacement folds, related to segmentation and fault growth process are common in the northern segment of the master fault. Many intra basin faults are formed sub parallel to the border fault zone (Figs. 8 and 9). Rollover structures (anticlines and synclines) developed within the hanging-wall of this segment

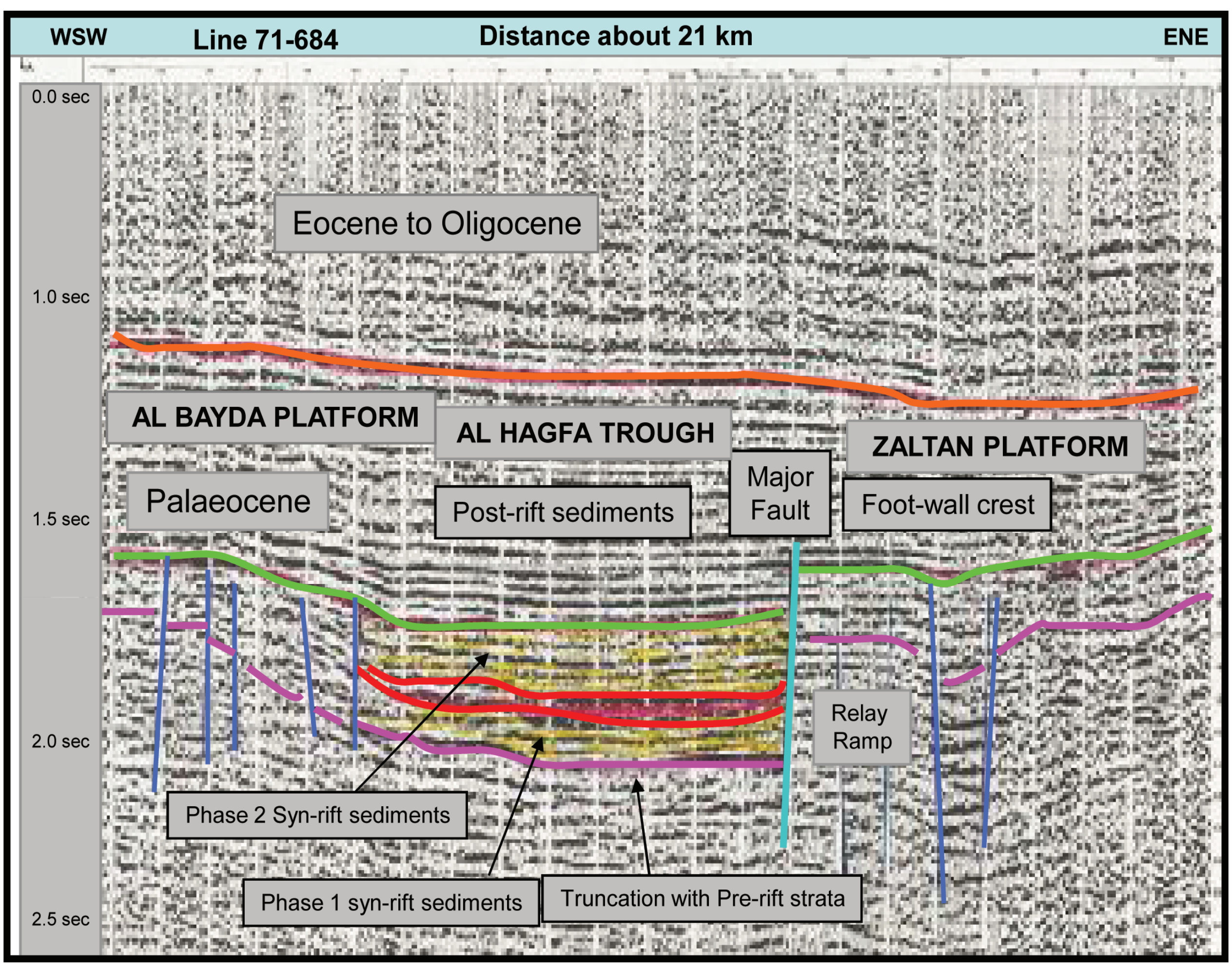

Fig..7. Interpretation of line 71-684 depicting faults, ramp at relay zone, stratigraphic, and structural configuration of a syn -rift wedges.

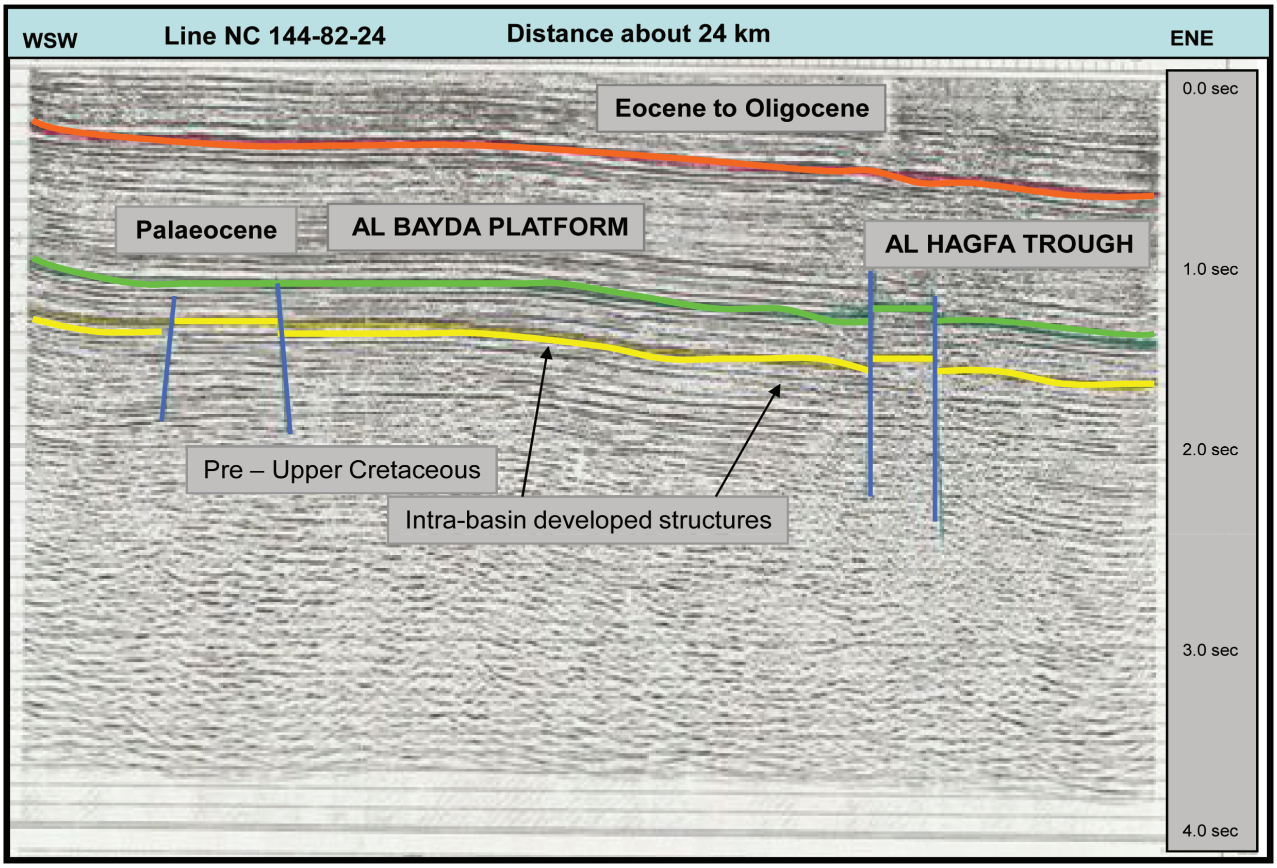

Fig. 8. Interpretation of line NC 144-82-024, showing horizons separating main time units with rollover structures (anticline like structures, synclines and folds) that have been developed with time and space during basin evolution.

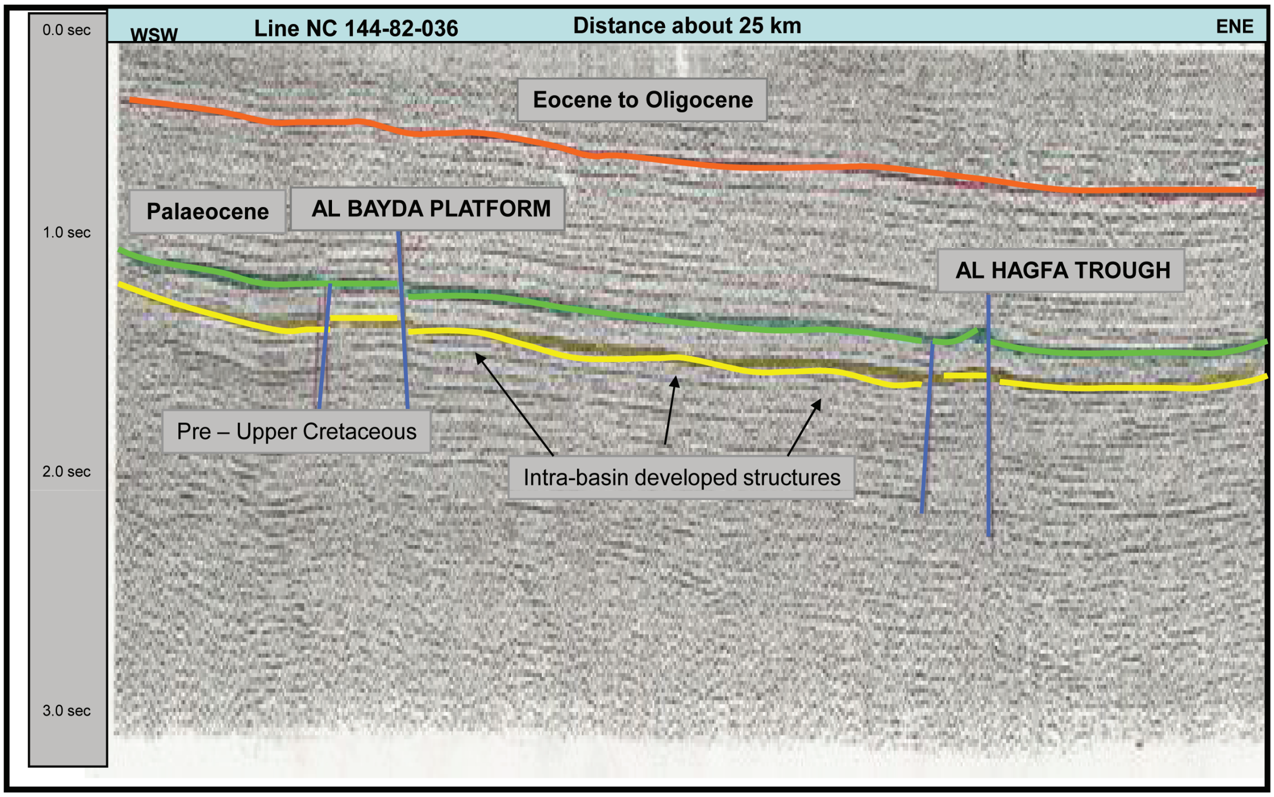

Fig. 9. Interpretation of line NC 144-82-036. It shows horizons separating main time units with rollover structures (anticlines, synclines, and folds) that have been developed with time and space during basin evolution.

mainly formed during radial propagation of this segment culminated with topographic changes associated with a transfer zone that form an important structural elements and has a marked influence on the area stratigraphy.

Computed forward models (Figs. 10 and 11) illustrate the nature and morphology of strata across the identified troughs and platforms. The models show typical sedimentary growth across the fault zone which in general is sufficient to produce structures similar in geometry and magnitude to the observed features.

Generally, in any extensional regime compaction is one of the most important mechanisms in the deformation of normal fault hanging-walls even in areas where basement is not involved in the faulting (Andrew, 1994). Despite the difference in location between gravity profiles and seismic sections, the gravity models (Figs. 10 and 11) and the interpreted seismic section (Fig. 7) show evidences of syn-depositional features and compaction within the hanging-wall. Under certain circumstances anticlines in the hanging – wall can also form as a sole result of compaction. The mode of extension has important consequences for the Cretaceous hydrocarbon entrapment associated with the rifted province of Al Hagfa Trough. It can be observed from the seismic section (Fig. 7) and the horizontal gradient map (Fig. 5) that there is a system of southwest-dipping, sub-parallel intrabasinal normal faults offsetting Cretaceous - Tertiary sediments and perhaps separating fault segments at the relay zones.

Evaluation of the main structures suggests that Al Hagfa Trough area could be reconsidered as a target for future hydrocarbon exploration. The major gravity minima over the trough can best be accommodated by a major rift zone, filled with probable Cretaceous and younger sedimentary sequences of about 3 - 5 km thick. The gravity minima associated with the bathymetric highs of the trough are best explained by recognizing that it is a thick sequence of dominantly sedimentary rocks, probably deposited on thinned continental crust bordering the rift.

Brief Review of Magnetic Data

The preliminary produced maps (Figs 12 and 13) show northeast – southwest and east - west striking magnetic highs that extended across Zaltan Platform and Al Bayda Platform respectively. It seems that the anomalies produced by these highs are caused by high magnetic rocks, probably coincides with the locations of magma tracks. In addition to that many northerly and easterly trending magnetic lineaments are visible on the total intensity magnetic maps (Figs

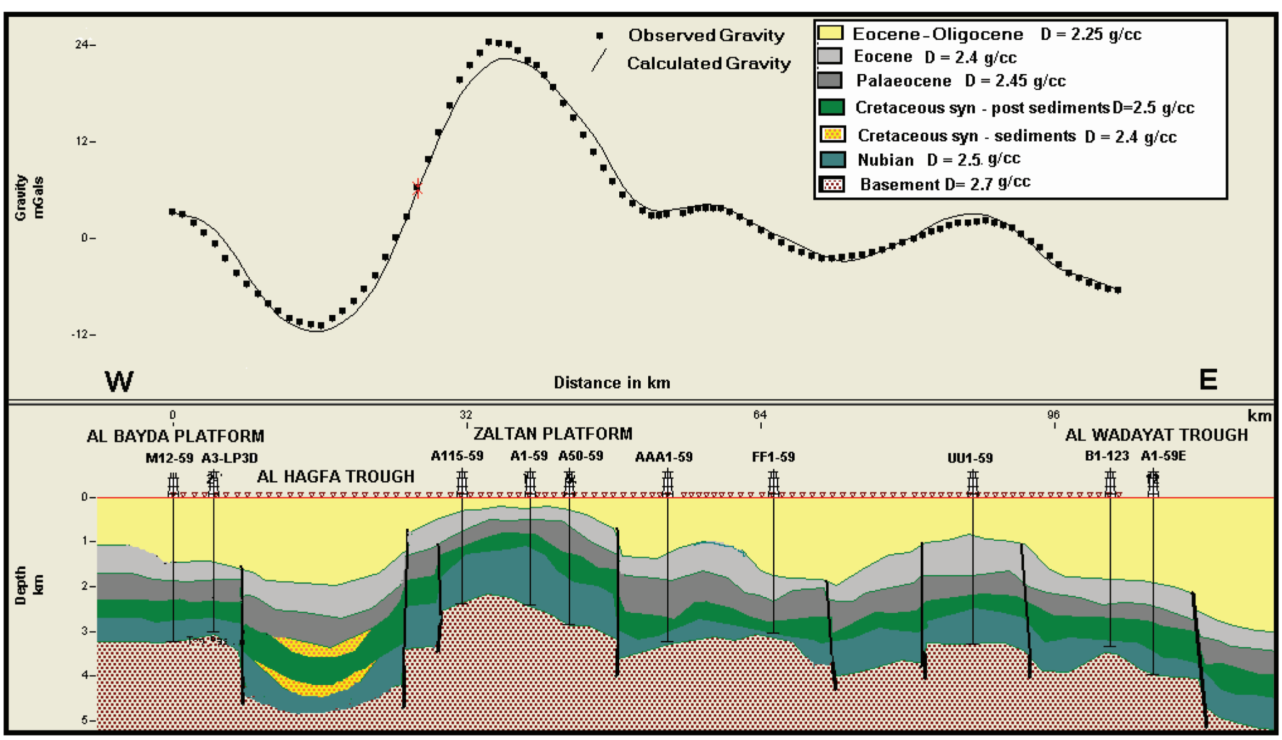

Fig. 10. E-W residual gravity model along profile A – B, showing major and minor faults with subsurface cross section across the mapped platforms and troughs.

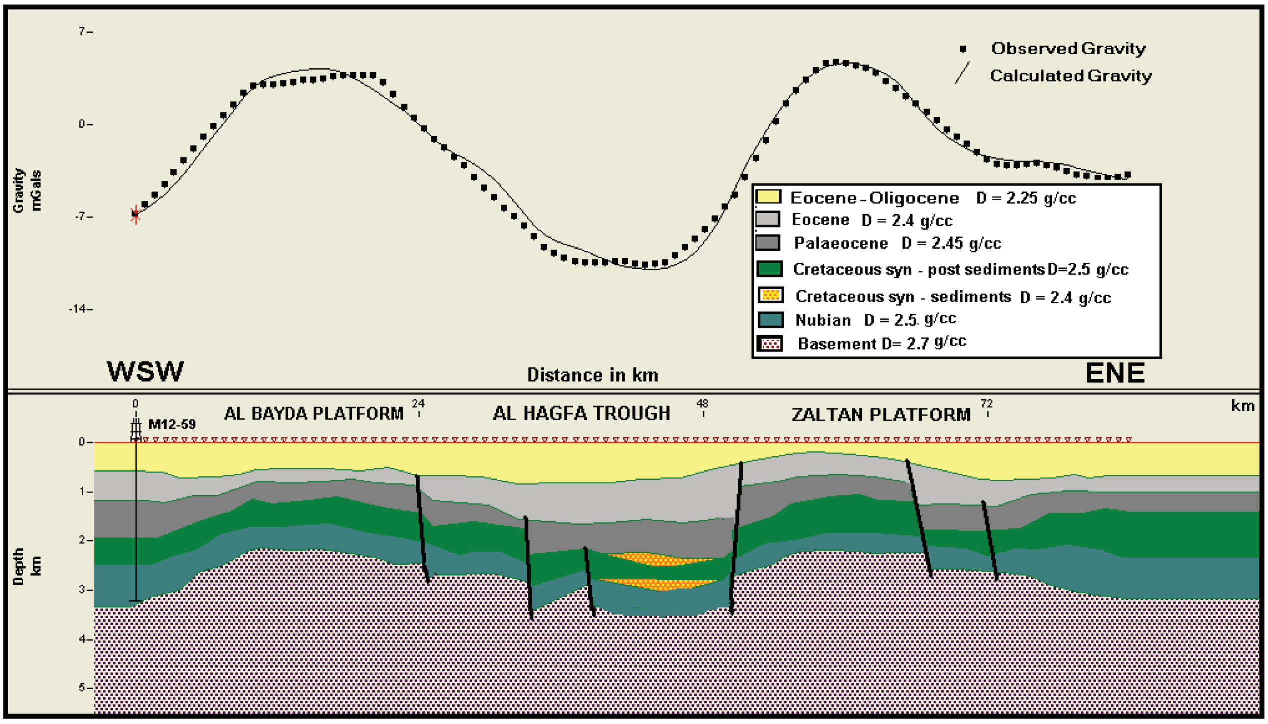

Fig. 11. ENE-WSW residual gravity model along profile C – D, showing major and minor faults with subsurface cross section across the mapped platforms and troughs.

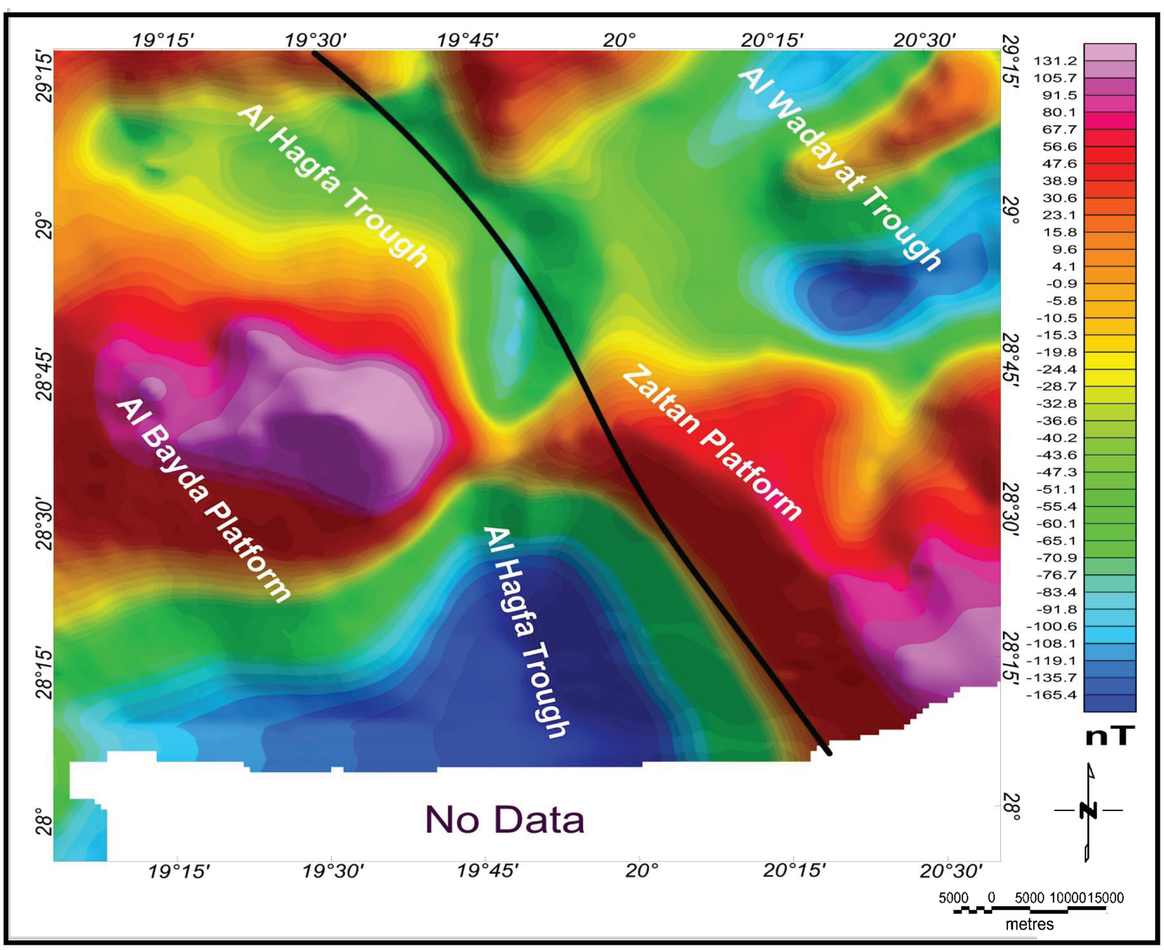

Fig. 12 Total magnetic intensity map of the study area.

12 and 13). The lineaments probably follow lithological contacts in the basement and/or basement shearing trends. Northwest-southeast and northwest-southeast fault trends can be seen to offset the lineaments.

The diagonal fault represents a major fault zone that was traced on the gravity maps. Further work is needed to confirm these preliminary interpretations.

DISCUSSION

Fault Geometry and Graben Evolution

The discussion that follows introduce the implementation of gravity and seismic dataset to locate major structures (horst and graben features) and associated faults evolved during rift evolution in part of the Sirt Basin, (Al Hagfa Trough region and the nearby areas).

The interpretation and modeling of the main structures were accomplished using Bouguer gravity and seismic data. Several trends related to the basin evolution were identified: (1) a northwest to southeast trend, indicates northeast to southwest extension throughout the study area, and (2) a predominantly northeast to southwest directed trend, indicate northwest to southeast extension, primarily in southern regions.

The study area is characterized by a dominant northwest-southeast trend. This is clearly evidenced from the horizontal derivative of the residual Bouguer gravity, with east-northeast and west-southwest trends takes over, characterized by broad gravity highs and lows. This is mainly related to the development of the tectonic zone.

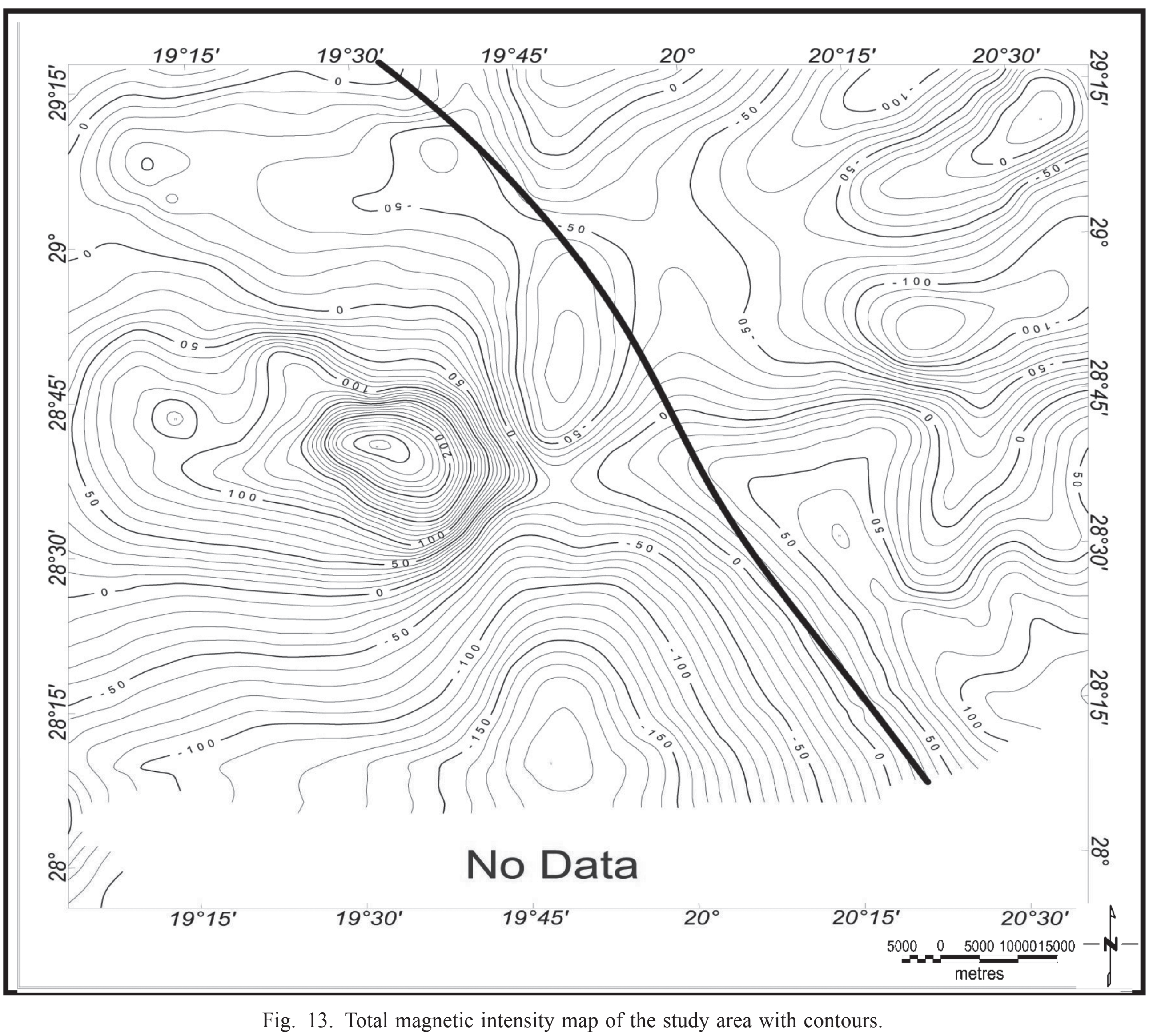

Fig. 13. Total magnetic intensity map of the study area with contours.

The identified major fault zone located between the Zaltan Platform and Al Hagfa Trough was formed by a system of large normal faults, interpreted to be mostly planar, basement – involved fault segments linked together by transfer zones. It is about 150 km long, composed of three 45 – 50 km long normal fault segments trending N - S and NE - SW direction and dipping towards the west direction. The master fault appears in the total horizontal gradient map with different arrays. It is trending NW – SE at the northern portion of the study area with evidence of splays or horizontal displacement along transfer zone, and N – S trend formed at the southern portion due to segment tilting.

As observed from the seismic data and the gravity models, the fault segments separate pre-rift lithologies in the foot-wall from the syn-rift sequences in the hanging- wall. The segments are tipping out along strike with evidence of linkage along the immediate hanging-wall of the fault block at probably breached relay zones.

A series of intra-basin structures can be observed that have axes mainly parallel to the fault zone (transverse folds, anticlines….etc) which probably formed during fault growth process.

Structures Evolution

The material movement along the strike of the hanging-wall is supported by the thickness of the syn-rift contraction sedimentary sequence (McClay, and Scott., 1991, Yamada and McClay, 2002). It is considered that the lower part of Al Hagfa Trough is associated with Cretaceous – Palaeocene syn-tectonic sequences subsequently buried by post-rift sediments. The syn-rift sequences in the wedge forming fault block can be divided into lower and upper sequences with onlap surfaces between them suggesting that there may have been two rift phases. Onlap relationships can sometimes be defined from seismic data, particularly at the base of the lower syn-rift sequences.

From the gravity models and the seismic sections, it has been considered that Pre-Upper Cretaceous section (Nubian) is probably truncated with basement as pre-rift sedimentary section. This needs more future work using high resolution data, because the master fault seems to be segmented below the seismic resolution.

CONCLUSIONS

- The Gravity maps indicates that the study area is marked with elongated gravity maxima and minima trending NW-SE showing a strong correlation with the structural highs (associated with platforms) and the structural lows (associated with sedimentary filled troughs) known from drilling. The maps also shows that Al Hagfa Trough is marked by a long wavelength negative gravity anomaly and very steep gravity gradients which delineate faults along the edges. The horizontal derivative enhances many of the more subtle trends that are masked in the anomaly maps.
- The study area reflects high frequency anomalies consistent with the horst-graben systems and relatively shallow to deep basement depths.
- We investigated structural and stratigraphic signatures related to rifting. Such investigations considered fault initiation during the development of the study area.
- Syn and post tectonic sequences can be resolved from scarce seismic sections within the study area. For example the 2D seismic sections show that truncation of pre-rift strata together with thinning and onlapping syn depositional strata onto fault scarp suggest that the area has experienced a series of rifting episodes during basin evolution.
- Nature of faulting and later subsidence might have had an effect on charge pattern (fetch areas vs. charge volumes, as well as bypassed areas).
- Intra basin transversal structures either related with accommodation zones or further block movement can be interesting for intra-trough hydrocarbon entrapment.
- Transfer and accommodation zones on the platform areas might have affected migration pattern along with interesting main margin faults.
- Enhancement of existing magnetic data will shed more light on basement and anorogenic magmatic rocks configuration which will enrich our understanding of the geology of Sirt Basin.

ACKNOWLEDGEMENTS

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