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# Structure of the Ajdabiya Trough, NE Sirt Basin-Libya, Derived from Gravity and Magnetic Data

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**Abstract:** ***This paper presents an interpretation of integrated potential field dataset from Ajdabiya Trough, northeast Sirt Basin Libya. The trough is a ~7,000 m thick aborted NW-trending rift that was formed during the Early Cretaceous time (the collapse of Sirt Arch). The study aimed to assess the role of basement structures in the development of the Ajdabiya. Our results indicate that the major fault systems of the Ajdabiya Trough were superimposed on Precambrian Pan-African basement fabric. A NW-SE trending structures are predominant, along with subordinate of E-W trending features parallel to structures formed during early rift stage. The results of the combined gravity and magnetic modelling reveal an extended graben structures that comprises an elongated depocentres that are separated by intra-rift horsts and bald basement highs. In addition, part of the Moho topography within the study area iscontrolled by a shear zones and developed during periods of crustal extension during the Mesozoic time. The gravity and magnetic signatures, suggest that Mesozoic – Cenozoic mafic intrusive possibly constitute the basement blocks and possibly play a significant roles during subsequent stages of extension and fault reactivations. ENE-WSW trending shear zones as it appears on the gravity and the magnetic maps may have facilitated the emplacement of Pre-Cambrian intrusions and accommodated NW-SE extension within the Ajdabiya Trough and reactivated pre-existing fabric during the EarlyMesozoic time.***

**Keywords:** Potential field, Fault system, Mesozoic rifting, Ajdabiya Trough, Sirt Basin

## 1. Introduction

The Ajdabiya Trough with its thick Cenozoic section is located on the northern margin of the onshore Sirt Basin (Figure 1) close to the continent-ocean transition that connects stretched North Africa continental crust in the south with Central Mediterranean oceanic crust to the north (Casero and Roure 1994; Gaina et al., 2013). It is considered to be the deepest part of the Sirt basin rift domain (~ 4 – 10 km), (Hallett, 2002; Abuhajar and Roohi 2003; Guiraud et al., 2005; Capitanio et al., and 2009), and characterized by NW-SE cross-cutting structures which reflect basement grain and/or location of major rift faults within the Mesozoic cover. The trough also lies close to areas of Cenozoic volcanic activity (e.g. Ade-Hall et al., 1974) (Figure 2). It is also situated close to a highly deformed area in northeast Libya (Cyrenaica Platform (Figure 1), that severely deformed by folding and thrusting during the Late Cretaceous (Santonian) time (ca. 84 Ma) (e.g. Anketell et al., 1996; El Arnauti et al., 2008) and localized uplift during the Paleogene between ~60 and 50Ma, possibly ascribed to a strike slip component (Bosworth et al., 2008).

Continent–continent collision between the African and the Eurasian plates began about ~170 - 200 million years ago, and it has resulted in subduction of the African Plate and thickening of the underlying crust (Dercourt et al., 1986; Savostin et al., 1986). This affected major parts from Sirt Basin including the northern part of the Ajdabiya Trough (Figure 2), which was subsequently affected by NE-SW crustal extension (Schäfer et al., 1981; van der Meer and Cloetingh, 1993), and formed NW-SE trending structures presumably prevailed by upwelling of high density materials along deep fault zones in middle and lower crusts (e.g. Cloetingh and Van Wees, 2005), which induce high gravity anomalies. This subsequently followed by thinning of the continental crust beneath the northern part of the Ajdabyia Trough.

Rifting of this thinned continental crust led to the emplacement of volcanic intrusions, sills with oceanic crustal characteristics (e.g. Ahlbrandt, 2001). The region is also characterized by high heat flow, and mildly deformed (stretched) continental crust (e.g. Nyblad et al., 1996; Burwood et al., 2003; El Arnauti et al., 2008).

The NE-SW tectonic extension within the northern part of the Ajdabiya Trough is more recent than southern parts, which is possibly related to the late stage of formation of the Sirt Basin (McKenzie, 1970; Jackson and McKenzie, 1984a, b, 1988). This hypothesis is supported by independent evidence of magmatism and deferential faulting during the Late Cretaceous - early Eocene period (~ 70 - 50Ma), inducing large extension in the basin (Capitanio et al., 2009), it could explain the stretching during the Paleogene, although this process could possibly account for the Neogene evolution of the Sirt domains, when tilting, regional subsidence and magmatic activity took place (Ade-Hall et al., 1974; Schäfer et al., 1981; van der Meer and Cloetingh, 1993). Crustal structure and therefore subsidence may have further controlled Cenozoic tectono-magmatic cycles through temporal variations in melt supply throughout the Sirt Basin (Ade-Hall et al., 1974; Gumati and Nairn, 1991; van der Meer and Cloetingh, 1993).

In Sirt Basin, the term “basement control” commonly is used as an explanation for long, linear or comparably structural trends within the sedimentary section and as a cornerstone of certain play concepts in the petroleum industry (e.g. Vail, 1991; Hallett, 2002). Recent drilling within deep troughs such as the Ajdabiya Trough suggests that clastic reservoirs beneath the carbonate reservoirs have good potential (Hallett and El Ghoul, 1996). As a consequence there are important differences in stratigraphy and structure between different parts within the Ajdabiya Trough, which have substantial influence on regional interpretations of some unit distributions and on petroleum occurrence. With the completion of public domain gravity and magnetic coverage in the Ajdabiya Trough area (e.g. The Libyan Gravity Compilation Project, 2001), it is important to know how; basement and deep crustal structures have influenced the structure and stratigraphy of the sedimentary section.

Results of previous gravity and magnetic studies in Sirt Basin were presented by view authors, (Essed, 1978, El-Butroukh and Zentani, 1980, Suleiman et al., 1991). They all argue that the gravity and the magnetic anomalies in the area have been significantly influenced by lower crustal structures and magmatism formed during the Early Cretaceous - Tertiary in response to crustal extension causing active subsidence resulting in the collapse of post-Hercynian structures and movements along active basement faults (e.g. Goudarzi 1980; F.D. van der Meer, 1993; Hallett, 2002).

The present-day North Africa was located along the southern passive margin of Neo-Tethys and was characterized by the development of extensional basins in Libya and Levant (probably transtensional basins) (Schandelmeier and Reynolds, 1997). The margin of northeast Africa, from the Gulf of Sirt to the Levant, was traced according to recent seismic refraction (Vidal et al., 2000; Netzeband et al., 2006) and surface wave dispersion data(Di Luccio and Pasyanos, 2007), which indicate that the eastern Mediterranean is floored by thinned continental crust. The Ajdabiya Trough recorded the largest continuous subsidence in the whole Sirt rift, thus offering the most significant estimates of its stretching history (Gumati and Nairn, 1991; Abadi et al., 2008). For instance variations in the produced Bouguer gravity and magnetic anomalies compared to the transitional crust within the Ajdabiya Trough possibly indicate a higher amount of stretching for this crustal segment. This could be associated with changes in Tethyan oceanic crust and inversion of previously subsiding rift basins on the southern Tethyan margin (e.g. El Hawat and Abdulsamad, 2004).

The objective of this study is to link and integrate cross-sectional (2D seismic reflection) and gravity/magnetic data in order to compare deformation fabrics of basement and overlying sedimentary rocks and assess whether the fabric of the basement has influenced the sedimentary section.

We integrate gravity and magnetic data in order to map shallow features and deep crustal structures that controlled the structural framework of the trough and are possibly related to reactivated rift faults and shear zones of Pan-African and post Hercynian ages (e.g. Conant and Goudarzi, 1967; Burke and Dewey, 1974). Therefore, effective methods are needed to study fine crustal structure under the Ajdabiya Trough region. Here, we will apply effective anomaly separation and density/magnetic susceptibility modelling methods in order to study crustal structures and Moho topography by restriction of the most recent geological and geophysical data.

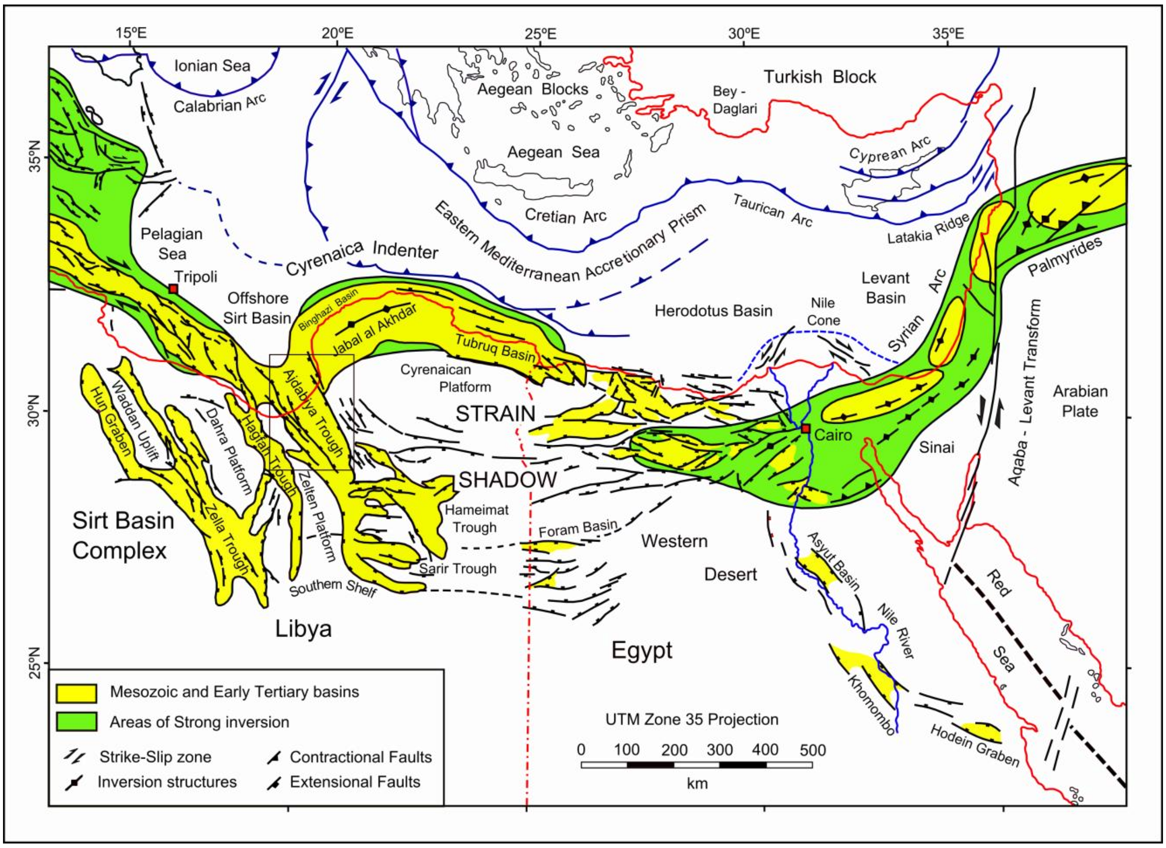


**Figure 1:** Tectonic setting of northeast Africa and the eastern Mediterranean collision zone, with location of Ajdabiya Trough (black rectangle) in the NE periphery of the Sirt Basin, from Bosworth et al., (2008)

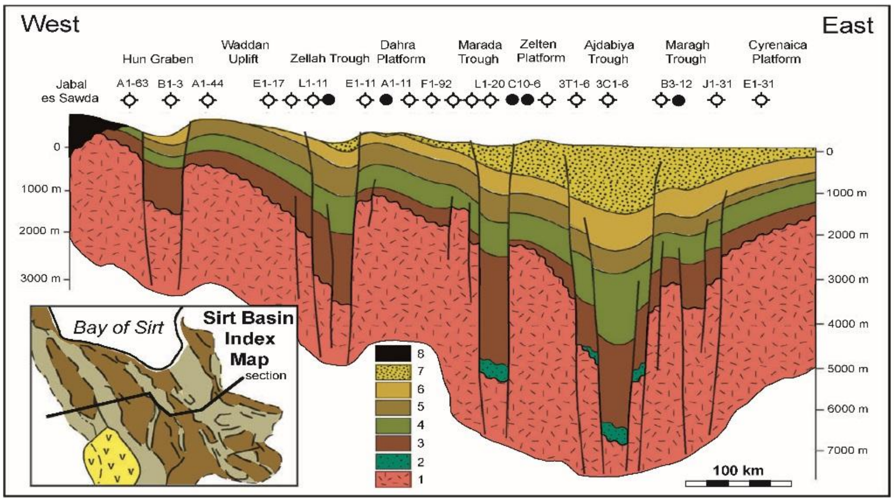


**Figure 2:**(a) Diagrammatic geological cross-section across the Sirt Basin, modified from Abuhajar and Roohi (2003), re-drawn from Guiraud et al., (2005), showing remarkable thickening in strata caused by dramatic subsidence and movement along major bounding faults in the Ajdabiya Trough. (1) Precambrian basement and Paleozoic quartzites; (2) Early Mesozoic(?) sandstones; (3) Late Cretaceous; (4) Paleocene; (5) Early Eocene; (6) Middle Eocene; (7) Late Eocene to Recent, (8) Cenozoic volcanics. Onset map shows the location of the cross-section, the brown and pale green colors are horst and graben features respectively and the yellow color indicates the Cenozoic volcanic

## 2. Geological Background

The Phanerozoic tectonic events of Libya are the product of the plate movements of Africa, influenced by Late Precambrian Pan African trends (e.g. Guiraud, and Bosworth, 1999). Most of these tectonic events are associated with the more mobile Late Precambrian accretionaryterranes (Boudjema, 1987; Vail, 1991; Black et al., 1994).

Basement structures in Libya is considered to be an inherited Pan-African and Palaeozoic structures trending N-S, E-W, and NE-SW and have gentle to moderate dips to the southeast. However block faulting occurred along NNW-SSE to NW-SE zone of weakness cross-cutting earlier Palaeozoic structures at a high angle but possibly parallel to some of basement shear zones (Anketell, 1996; Coward and Ries, 2003). The N-S trends were initiated as Pan-African shear zones that delineate Precambrian terrane boundaries. These long-lived basement structures have been reactivated throughout the Phanerozoic (Bumby and Guiraud, 2005).

The Hercynian orogeny occurred during the Late Carboniferous to Early Permian (400-280Ma) producing a broad arching area within the Sirt Basin (e.g. Hallett & El Ghoul, 1996; Hallett, 2002) and caused variable metamorphic and reworking of older basement rocks (El-Makhrouf, 1996).

The most prominent event in Libya is the Sirt trans-extensional system associated with the African rift system that has its roots deep in the Pan-African N-S and E-W trends and an associated sub-plate adjustments (e.g. Maurin and Guirand, 1993; Selley 1997; Gras and Thusu 1998; Ziegler et al., 1999). This event resulted in the subsidence along three main directions, NNW, NNE and E, producing important depocentres.

The Sirt basin part of the Tethyan rift system, with significant rifting and syn-rift sediment deposition in the Permo-Triassic to Early Cretaceous and post-rift deposition in the Oligocene – Miocene (Coward and Ries, 2003). The basin geometry appears to be controlled by structural heterogeneities or weaknesses within the basement (e.g. Pan-African shear zones). The distance from the active plate boundary to the weak zone played a significant role in the structural development and reactivation of pre-existing faults(e.g. Brede et al., 1992; Craig et al., 2008).

There is a consensus that regional and local tectonic influenced sedimentation in theNE Sirt Basin has played a significant role in the development of the Ajdabiya Trough structural styles (e.g. Baird et al., 1996; El Arnauti et al., 2008). The location of the Ajdabiya Trough close to the Africa-Europe plate boundary zone means that the basin evolution is likely to have been characterized by active tectonic deformation, in addition to more typical sag-basin processes such as thermal subsidence and differential compaction (Skuci, 1994; Baird et al., 1996).

The structure of the Ajdabiya Trough (Figures 1 and 2), especially in the deeper part is not clear. It has been described by Parsons et al., (1980) that it is a half graben characterized by different structural patterns and styles along it is margins, the difference in the nature of faulting on opposite sides of the trough may be responsible for the structural asymmetry (Figures 3 and 4) (Baird et al., 1996). The northern margin of the trough is defined by a horst structure known Al Brayqah High (Hallett and El Ghoul, 1996), which is covered with Paleocene carbonate rocks and thick sequences of Oligocene - Miocene shale (Wennekers et al., 1996). The southern margin (Figure 3) is characterized with a gentle slope (ramp margin) with small faults down to the basin. The western side of the trough close to the Al Jahama Platform (Figure 1) is very little known, but it is believed to be a sharp faulted margin (Hallett, 2002). The eastern flank of the trough is more complex, it became the main source for siliciclastic sediments starting in the latest Oligocene (El Hawat et al, 2007) with uplift followed by tilting through the early Miocene. The North-eastern margin abuts against the Cyrenaica and the Amal Platforms, with a series of terraces which may represent relay-ramp faulting (Hallett, 2002).

The Ajdabiya Trough was formed during three main tectonic phases, as recorded in the Sirt Basin. During the first phase the trough was a cratonic basin to a passive margin in the North African Margin (NAM) that formed as a result of late Precambrian-early Paleozoic extension and continental break-up. Subsequent thermal contraction of a rifted lithospheric mantle drove subsidence and sediment accumulation during the Paleozoic (Gumati, 1984). The second phase of evolution is recorded in the Devonian through early Jurassic strata that may represent a number of loosely constrained tectonic environments and basin subsidence. Dynamic topography (buoyancy contrasts in the mantle) may have been an important contributing factor to subsidence at this time (Holt. 2012; Galushkin et al., 2015).

During the Mesozoic to early Cenozoic (Late Cretaceous to Paleocene), third phase records the development of rift basin cycles accompanied and concurrent with differential and successive fault activity resulting in fault-controlled subsidence and rejuvenation of faulting during Early Eocene time (Gumati and Nairn,1991; van der Meer and Cloetingh, 1993).

During the Late Eocene a compression event caused regional tilting and subsidence in Ajdabiay Trough (e.g. van der Meer and Cloetingh, 1993; Baaske et al., 2013), aside from that event, the Late Eocene onward was a period of minor tectonic activity terminated growth of the rift fault system which was dominated by isostatic forces and uplift throughout the Cenozoic period (Capitanio et al., 2008).

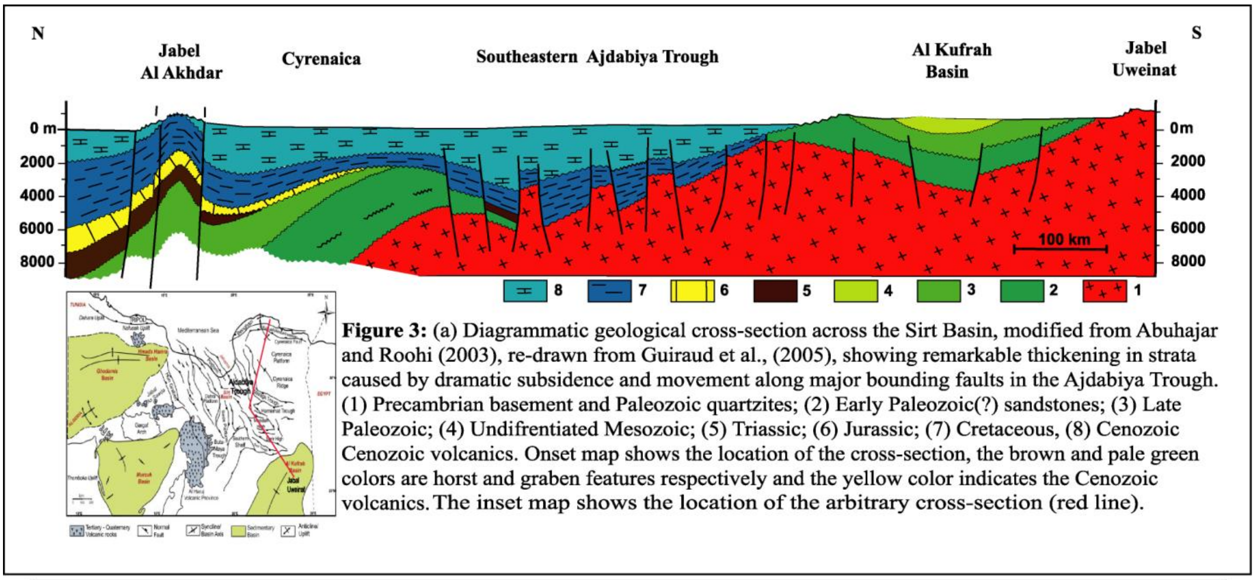


**Figure 3:** (a) Diagrammatic geological cross-section across the Sirt Basin, modified from Abuhajar and Roohi (2003), re-drawn from Guiraud et al., (2005), showing remarkable thickening in strata caused by dramatic subsidence and movement along major bounding faults in the Ajdabiya Trough. (1) Precambrian basement and Paleozoic quartzites; (2) Early Paleozoic(?) sandstones; (3) Late Paleozoic; (4) Undifrentiated Mesozoic; (5) Triassic; (6) Jurassic; (7) Cretaceous, (8) Cenozoic Cenozoic volcanics. Onset map shows the location of the cross-section, the brown and pale green colors are horst and graben features respectively and the yellow color indicates the Cenozoic volcanics. The inset map shows the location of the arbitrary cross-section (red line).

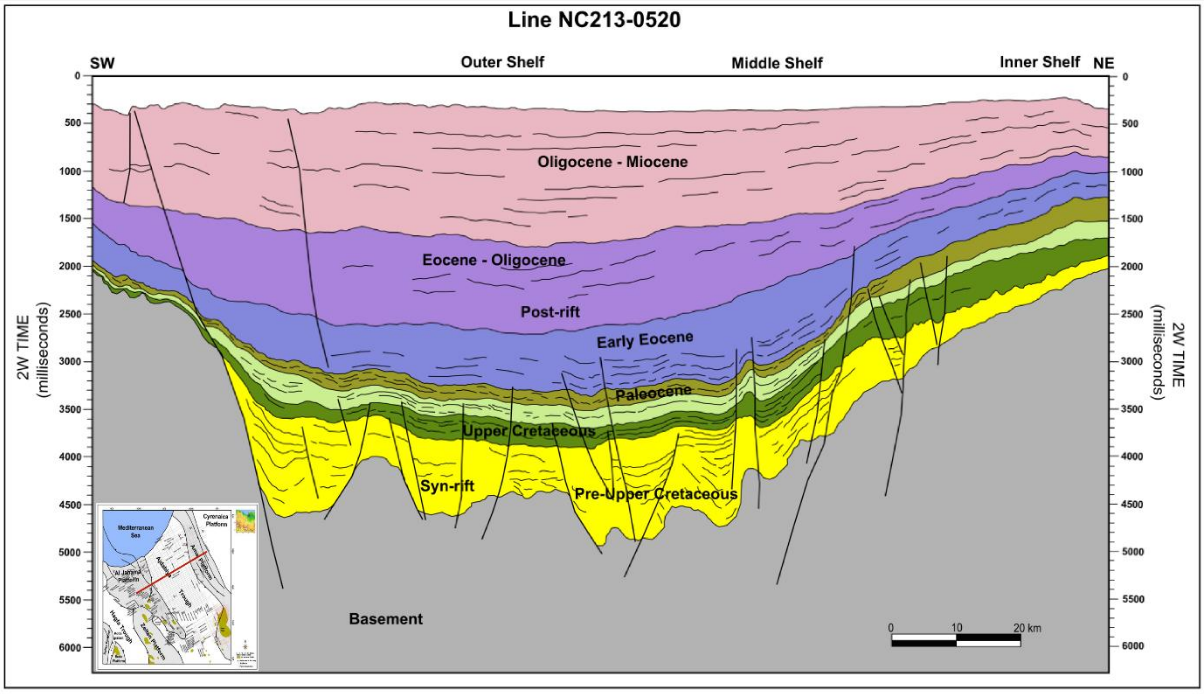


**Figure 4:**SW - NE transect line **05-NC213 0520**, across the Ajdabiya Trough show the basement topography and the fault style within the study area. The line also demonstrates the remarkably sediment accumulations and the uniform subsidence that occurs throughout the Cretaceous and Cenozoic. Inset box show the line location

## 3. Basement Structure

The basement rocks of the Sirt Basin are largely undifferentiated stratigraphy due to the lack of abundant data and geochemical analysis, but intrusive rocks make up the largest part of the crystalline basement series (Busrewil et al., 2008). The petrographic character of the crystalline basement also points a metamorphosed quartzite sediments, probably of Ordovician and partly of Cambrian age (Tawadros, 2001). Isotopic ages have been obtained from variety of igneous and metamorphic rocks in the Sirt Basin, almost give ages within the range 670 to 460 Ma. Several wells incidentally have encountered Jurassic and early Cretaceous granites which have been dated isotopically (Hallett, 2002).

Results of extensive drilling connected to petrography and geochemical studies of the southern Ajdabiya Trough (Busrewil et al., 2008), suggest that the basement of the Ajdabiya Trough includes pre Pan-African metamorphic schists, Pre-Cambrian crystalline schists and granitoids belongs to syncollosion indicative of plate margin setting with short emplacement history spanning the interval 500-560 Ma (e.g. Pegram et al., 1976; El-Makhrouf, 1988). According to the study of Busrewil et al., 2008, the basement of the northern part of the trough is comprised of mica-schists, graphite mica schists, local garnet-bearing mica-schists, meta-greywackes and meta-arkoses. These rocks are usually lithostratigraphically ranked to the Late Proterozoic and Cambrian, and to the Middle and Late Cambrian (e.g. Barr and Weegar, 1972).

2D seismic data from the Ajdabiya Trough area (Figure 4) show that reflections can be observed within the pre-rift basement have yielded a number of spectacular examples of major Paleoproterozoic basement structures rising from a number of possible sourcesthat left a structural imprint during the assembly of the basement since the Hercynian orogeny (e.g. Jurdy et al., 1995; Hallett 2002; Bumby and Guiraud, 2005).

The structural grain of the basement in the Ajdabiya Trough also play significant role in controlling the overlying sedimentation patterns and related structures. For instance a NE-trending basement structural grain influenced the development of NE-trending Triassic-Jurassic growth faults in the Ajdabiya Trough and the adjoining Cyrenaica Platform (e.g Rossi et al., 1991; Thusu 1996; Gras and Thusu, 1998). These represents structural fabrics within the crystalline basement related to extensional and collisional fabrics, which consist of crustal scale shear zones that have maintained their coherence during ductile deformation and some are faults or fault zones offset the Mesozoic and Cenozoic strata. These faults were the focus of SE-directed Late Cretaceous and younger inversion (El Arnauti et al., 2008).

## 4. Data Set and Methods

### a) Gravity Data

A gravity data set covering the Ajdabiya Trough and the adjacent areas has been constructed from the Libyan Petroleum Institute (LPI) database using window data process, a tool supported in the Oasis Montaj software implying the extraction of any specific data from gravity and magnetic database starting with selecting a proper window boundary coordinates and then saving the extracted data in a new database. In general the gravity data that has been collected from different sources were merged and reduced to the mean sea level and processed to produce Bouguer gravity anomalies using the 1980 international gravity formula (Morelli, 1976), and estimated local bed rock density of 2.67 g/cm³. In the same context the density of the sediments has been obtained from different sources, (The Libyan Gravity Compilation Project, 2001) and from published works (Makris, and Yegorova, 2006, Casten and Snopek, 2006). In this regard, the rock density was estimated from density logs and core samples collected from the Sirt, Ghadames, Murzuk, Jefara and Cyrenaica areas (Essed, 1978). In addition to that we also used average density values from tables obtained from measurements of numerous rock, soil and mineral samples (Telford et al., 1990). Table 1 shows the density range for the common sediments and sedimentary rocks usually encountered in Libyan sedimentary basins.The density contrast was constructed by assuming a constant basement density of 2.67 g/cc and subtracting mean sedimentary densities as used in the 2D gravity and magnetic modelling.About 32144 gravity observations (Figure 5) represent the data set used in this study. There are a number of gaps around the Ajdabiya Trough area due to the lack of gravity surveys in these regions. Most noticeable are the gaps located to the southeast near Amal Platform and Rakab High, and to the northeast near Cyrenaica Platform.To overcome any voids in the data coverage, different interpolation techniques were employed during the image processing stage. After trying different grid intervals, the merged data were then gridded at an interval of 2.0 km and contoured using the minimum curvature technique (Briggs, 1974), in order to calculate the Bouguer gravity anomalies of the studied area. The minimum curvature method interpolates the data to be gridded with a surface having continuous second derivatives and minimal total squared curvature.The 2.0 km grid interval was selected based on the nature of (a) the space distribution of the gravity data, and (b) separation of regional and residual components of the gravity field.

| Rock Complex | Density [g.cm³] |
|---|---|
| Mid Eocene and Younger | 2.35 |
| Lower Eocene | 2.40 |
| Paleocene | 2.40 |
| Upper Cretaceous | 2.50 |
| Lower Cretaceous | 2.50 |
| Nubian | 2.54 |
| Carboniferous | 2.55 |
| Devonian | 2.55 |
| Silurian | 2.60 |
| Gergaf (Quartzitic Sandstone) | 2.74 |
| Igneous | 2.91 |
| Upper Crust | 2.74 |
| Lower Crust | 2.84 |
| Mantle | 3.20 |

**Table 1:** Density values of the main rock complexes used for the gravimetric modelling.The sediment densities were estimated based on published values and previous models, published values are mainly based on analysis of well logs (density and sonic) and core sample analysis from the Sirt, Ghadames, Murzuk, Jefara and Cyrenaica areas (Essad,

1978), (Libyan Gravity Compilation Project, 2001, Makris, and Yegorova, 2006, Casten and Snopek, 2006).

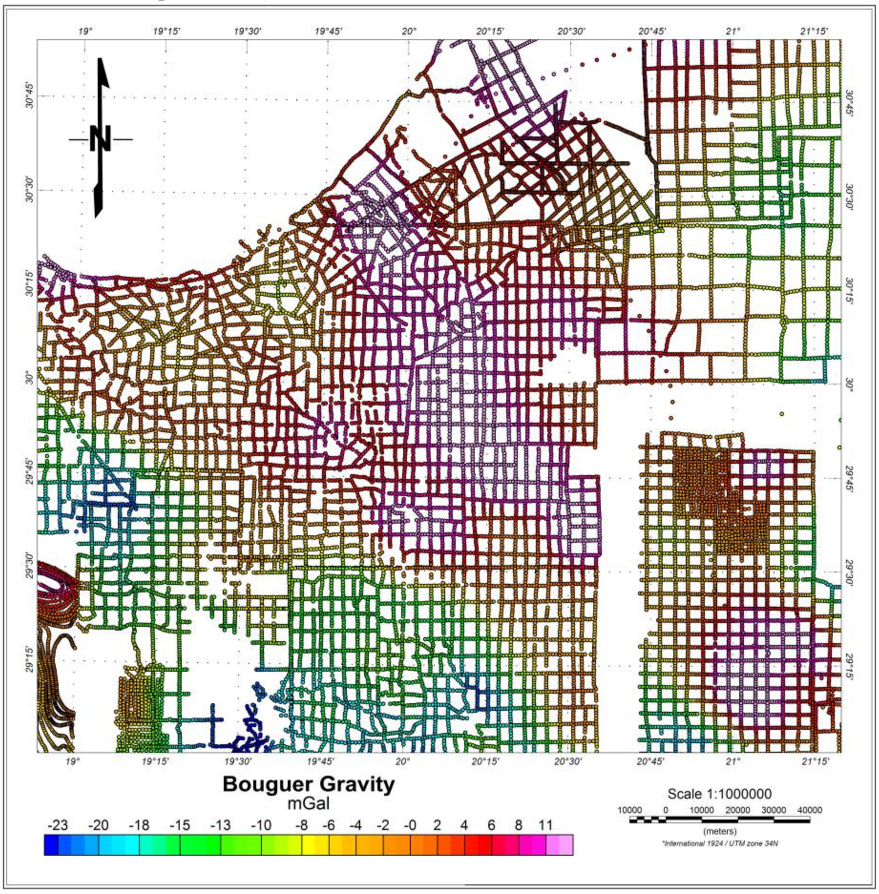


**Figure 5:** Map showing the distribution of the gravity data used in this study. The variable colored circles represent the station locations with different Bouguer gravity values according to the map color-code. The data were compiled from different surveys and mainly converted from maps to digital numbers. Other data obtained from contour maps (samples from this data showing at the SW corner of the map). Data obtained from the Libyan Petroleum Institute (LPI) as part from the Libyan Gravity Compilation project (2002)

**b) Magnetic Data**

The key component of the magnetic analysis in this study involved image enhancement of existing ground magnetic and aeromagnetic data sets acquired bydifferent survey companies (contractors) for the oil companies (clients) during theperiod from 1968 - 1977.

The same data were integrated with draped satellite magnetic data to form thecomplete magnetic data set for the purpose of the African Magnetic Project (AMMP)compiled by **GETECH** Company (University of Leeds, Dept. of Earth Sciences, Leeds - uk). This data enabled the interpretation to be extended over large areas of Libya where there was little well information. The AMMP was a compilation of all available airborne, ground and marine magnetic data for the whole of Africa. The data, which cover a variety of resolutions, vintages andtypes, were merged into a unified 1km grid at a constant 1km elevation above terrain.

After correction of the measurements for the temporal variations of the magnetic field, the total magnetic intensity (TMI) anomaly was deduced by subtracting the theoretical geomagnetic field or the International Geomagnetic Reference Field (IGRF) at each station (Barraclough and Malin 1971; Peddie 1983).

The TMI anomaly data were then upward continued to a height of a mean clearanceof 1 km before they were merged into a unified digital grid, which has a cell size of0.01 degree (i.e. 1. km). This grid enabled us to establish a reduction to the polemagnetic anomaly map (RTP) for the Ajdabiya Trough (Figure 7). The data providedby GETECH were already in residual form, after subtraction of the appropriate reference field.

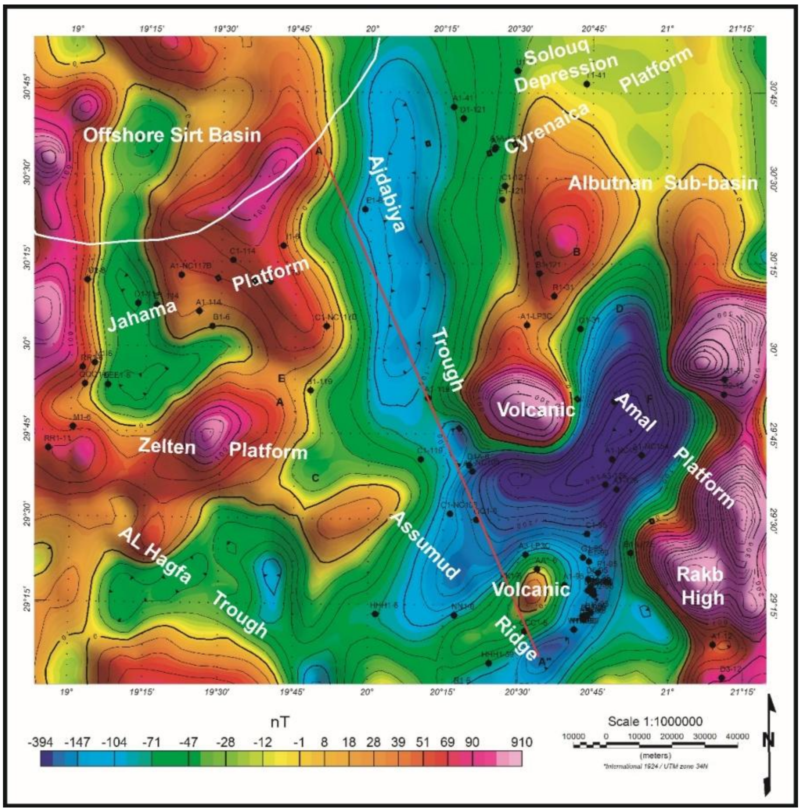


**Figure 7:** Reduction to the pole (RTP) magnetic map of the Ajdabyia Trough and the nearby regions showing the major structural elements superimposed over structural highs and lows of variable magnetic content. Contour interval is 10 nT.

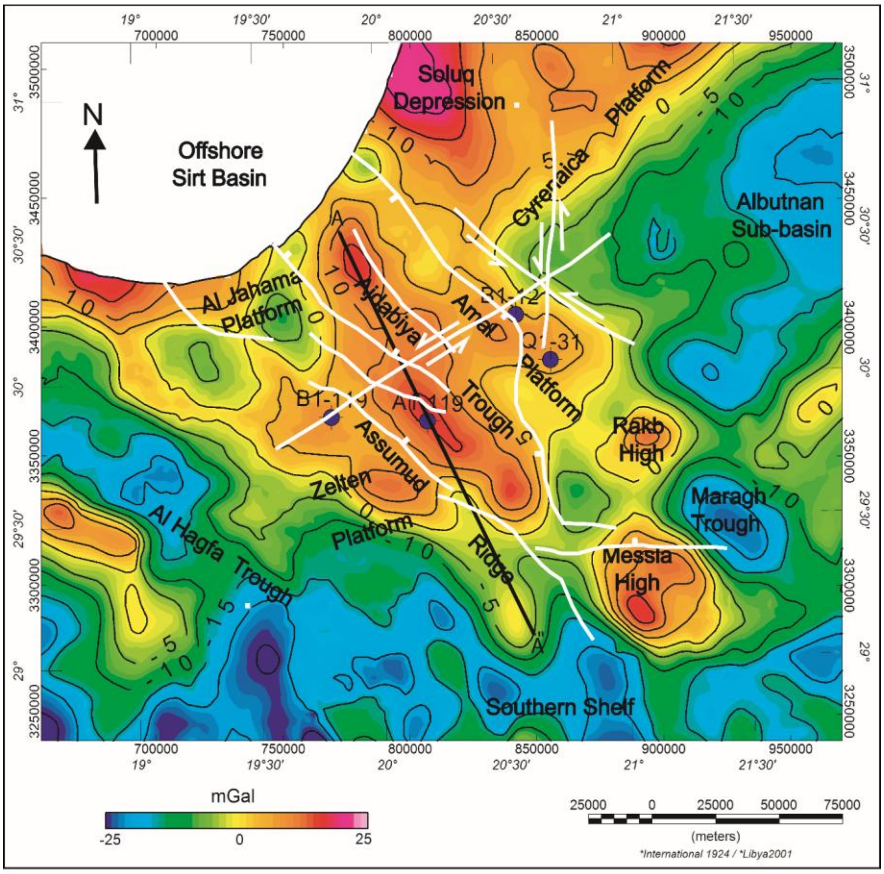


**Figure 8:** Bouguer gravity map of the Ajdabiya Trough and the nearby areas in simple display showing variable distribution of the gravity values related to major structural elements identified on the Bouguer map. Blue circles on the map are wells used in the gravity and magnetic modelling along profile AA". Strike slip faults identified on the map are indicated by lateral sense of movement (whiteslip vectors)

## 5. Gravity Analysis

### 5.1 An Overview of the Gravity Anomalies

The resulting Bouguer gravity map of the Ajdabiya Trough is shown in Figure 8. The gravity field includes several anomalies of relatively high and low amplitudes which are related to density differentiation of the rocks forming the earth crust (Riad, 1977). The map shows that mainly long wavelength anomalies related to large-scale deep seated structures are predominant. A gravity anomaly over the centre of the trough ranges from lows exceeding ca: 0 mGals (1 milligal = $10^{-5}$ m/s$^2$; yellow) to > ca: 15 mGals (warm orange).

The map show that four regions dominate the gravity field from east to west: (1) the gravity high (up to 23 mGals) in the Cyrenaica Platform and Solouq Depression to the northeast; (2) an arc shaped gravity low (relative, from 0 mGals to -20 mGals), which represents the easternmostsub-basins and troughs (Albutnan sub-basin, Maragh Trough); (3) an alternating group of gravity highs ranges from (0 mGals to +15 mGals) in the centre of the Ajdabiya Trough, and Al Jahama and Zelten Platforms to the west; (4) The low gravity up to -22 mGals southwest of Ajdabiya Trough, the area coincides with Al Hagfa Trough and part from the Southern Shelf.

The positive anomalies are mainly located within areas occupied by the Ajdabiya Trough complex as well as by the Rakb High to the south east and part from the Cyrenaica Platform at the north east. The positive anomaly over Cyrenaica Platform to the northeast (Figure 8) occurs over outcrops of Oligocene to Miocene carbonates (El-Hawat and Shelmani 1993).To the west of the Ajdabiya Trough a negative gravity zone is surrounded by regions of positive gravity anomalies parallel to the Al Hagfa Trough structural trend.

The patterns of the Bouguer gravity anomaly map (Figure 8) changes gently, implying a simple crustal density structure in the upper crust. The gravity anomalies reveal about 200 km long, elongated, NW-trending gravity highs with peak values of 0 mGals and amplitudes of 5-15 mGals. These variations were ultimately related to structuresformed during successive tectonic events. The substantial positive gravity anomaly can be seen in the centre of the map indicating that the upper crust in the central area is denser than the others.It is also interpreted to mark the position of a possible ridge identified by Hallett and El Ghoul (1996).The map also show an alternate high and low gravity anomalies lie from the west to the east, and are divided by many nearly paralleled major faults.Interpretation of 2D seismic data confirms that the Ajdabiya Trough area is affected by fault systems whose orientations are different owing to changes in tectonic regimes. The regional trend may also be influenced by a variation in sedimentary densities as a study of well logs from the Libyan basins (Essad, 1978) shows that in general the density of the sedimentary rocks increases from the SW (Murzuk region) to the NE (Cyrenaica).

The range of the Mesozoic - Cenozoic sediment densities in sedimentary basins is generally lower than that of most enclosing Palaeozoic sedimentary and crystalline rocks (Manspeizer et al**.,** 1989). Thus, medium to high negative gravity anomalies would be expected where the preserved strata in the basins are thick. Unlikely this is not the case in the Ajdabiya Trough area where low amplitude positive gravity anomaly is dominated and centred above the centre of the trough (Figure 8). However, the geometry of sedimentary basins is commonly not readily apparent from Bouguer anomaly maps because of the dominance of large-amplitude regional gravitational fields. During interpretation of the gravity data and after regional gradients of the gravity anomalies are removed using regional residual anomaly separation technique, the internal structures of the basins are usually discriminated, especially where there are major faults and thick sedimentary sections (Manspeizer et al**.,** 1989). Interpretation of basin geometry using gravity maps is further complicated by the presence in some areas of large volumes of intrusive bodies, dikes, and basalt flows (mafic / felsic basement); however, the large density contrast between these structures (density ~ 3.0 gm/cm³) and the Mesozoic - Cenozoic sedimentary rocks (density ~ 2.5 to 2.7 gm/cm³) facilitates meaningful analysis of intra-sedimentary volcanics (e.g. Busrewil et al., 2008; Witte, 2008).

In this study, the regional - residual field separation of the Bouguer anomaly has been studied using the “upward continuation filtering technique”. In this technique filtering separation using differential upward continuation (Paul et al, 1966; Jacobsen, 1987; Blakely, 1996) can be used to determine the gravity response arising from different depth intervals below surface.

Interpretations of lineaments and structures can be very important for structurally controlled deposits, intrusion-related deposits. Interpretation can be visual or semi-automated using some potential field filtering techniques (e.g., horizontal gradient and upward continuation).

Within the Ajdabiya Trough, localised NW-SE and N-S trending structural lineaments associated with positive gravity anomalies were inferred using upward continuation to 4000m level (Figure 9)which was the product of subtracting the field (data grid) upward continued 5000m from the field upward continued 4000m. The amplitude of these anomalies ranging from 2 mGals to about 9 mGals and are developed at the intersection of a NW-trending gravity high and an ENE trending gravity high to the north (Figure 9), possibly related to wrenching or shear zone that cut the Sirt Basin area and extended to the Cyrenaica Platform (South Cyrenaica Fault Zone SCFZ) (e.g. Anketell, 1996; El-Badrawy and Soliman, 2000; El Arnauti et al., 2008). The steep gradient and higher gravity values here suggest that this shear zone segment the crystalline rocks and the major gravity gradient reflects the juxtaposition of thicker Paleozoic - Mesozoic rocks within the study area.The gravityanomaly along the SCFZ is not obvious within the trough, but the fault cut off a highgravity anomaly trending NE-SW, accordingly the steep gravity gradient on the gravity map (Figure 8) is related to the SCFZ segment in the Cyrenaica area.The high gravity anomaly along the fault zone is related to the upwelling of high-density uppermost mantle materials along the fault.

The regional positive anomaly trending NW–SE, seems to represent the signature of dense rocks in the centre of the Ajdabiya Trough area. The regional structure is characterized by a broad positive gravity in the centrewith gradients increasing towards the northern part of the trough. It may be inferred from these observations that the basement is deepening towards the north of the region. Indeed, using gravity modelling and spectral analysis of gravity data, Spector and Grant, (1970)and Regan and Hinze, (1976) obtained the crustal thickness beneath the Ajdabiya Trough to vary from 26 km in the centre to 35 km in the east and west boundaries indicating that the crust is thinning towards the central part of the region.

The product of the upward continuation filter map (Figure 9) also shows that the study area is most likely characterized by large scale fault systems along with subordinate faults of variable trends and strikes. Seismic data confirm that these faults are mainly rift faults with different dips and strikes most likely basement reactivated faults and present within Early Cretaceous syn-rift sequences (e.g. Roohi, 1996b; Hallett, 2002).

To the north of the study area, the faults are trending NW-SE and NE-SW, while to the south the faults are predominantly trending NW-SE and E-W. The E-W trending faults may have initiated during the Early Cretaceous rifting (140-115Ma), probably in response to NS extensions along the edge of the Neo-Tethys, (Dercourt et al., 1993; Robertson et al., 1996; Guiraud, 1998; Guiraud et al., 2001; Bosworth et al., 2008), resulting in the development of E-W to ENE-WSW trending grabens and/or half grabens (Figure 8) that showed strong subsidence during the Early Cretaceous rifting (Neocomian-Barremian times), notably the Hameimat and Sarir in the south-eastern Sirt Basin (Figure 1) (Rossi et al., 1991; Gras and Thusu, 1998).

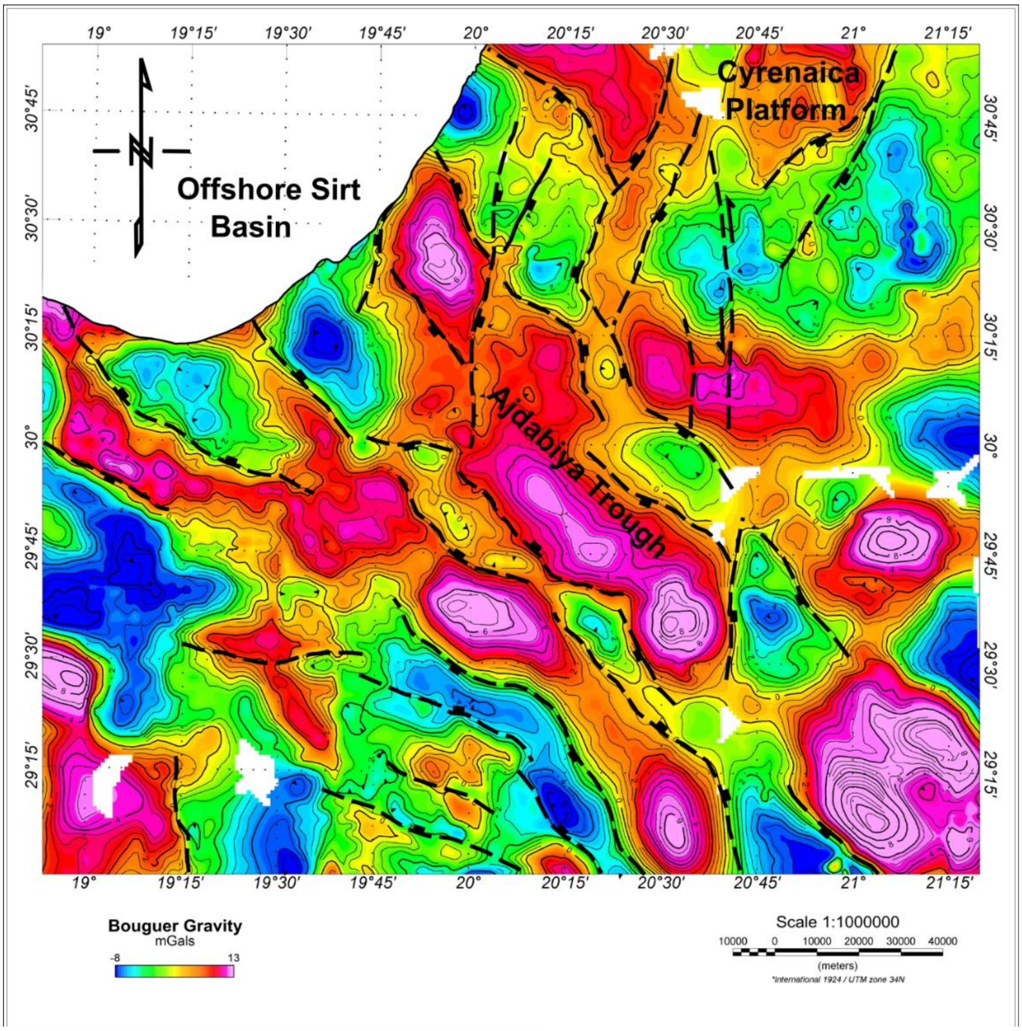


**Figure 9:** ResidualBouguer gravity map produced from upward continuation for interval ranging from 2 – 4km depth, showing main faults that cut the Cenozoic succession, along with an inferred strike slip fault at the NE part of the study area

## 6. 2D Gravity and Magnetic Modelling

In order to facilitate gravity interpretation, the gravity and magnetic responses of one geological profile has been modelled to attain a fit between calculated and observed gravity and magnetic using 2D modelling technique. The 2D modelling was performed with the GM-SYS modelling software, extension of the Geosoft Oasis montaj software package. GM-SYS Profile is a program for calculating the gravity and magnetic response of a geologic cross-section model. The software allows the user to digitize a profile from maps in Geosoft. In general, the extent (x-coordinate) and depth (z-coordinate) of the profile to be modelled and the Earth's gravity and magnetic field parameters (Strength, Inclination, and Declination) are defined. With the given coordinates a topography, gravity and magnetic profile can be extracted from geo referenced grids or maps.

The method of gravity and magnetic modelling enables us to test the conformity between the calculated gravity and magnetic response of modelled bodies in a vertical geological cross-section and the gravity effect measured in the field. In addition to the gravity anomalies assessed from the field measurements, densities of rocks, magnetic susceptibilities, shapes and the depth extent of geological bodies have been considered. To minimize the risk of non-realistic model solutions, the following sources were respected and integrated into the model: 1) The data from boreholes, especially of those situated near the line of the modelled cross-section; 2) any previous gravity or magnetic models such as those from the Sirt Basin and Cyrenaica Platform (Libyan Gravity Compilation Project, 2002; Witte, 2008); 3) rock densities obtained from previous studies such as those from (Essad, 1978; Libyan Gravity Compilation Project, 2001; Makris, and Yegorova, 2006; Casten and Snopek, 2006), magnetic susceptibilities are given parenthetically with some constrains from local and regional studies (Talwani et al., 1959; Blakely et al., 1999).

Within the Ajdabiya Trough area, we used the forward model to test the hypothesis that igneous intrusions are assumed to be another source of the positive gravity anomalies observed in the central Adjabiya Trough. This is because the igneous intrusions and their associated contact metamorphic rocks occur as isolated masses and mainly produce long wavelength anomalies on the gravity and magnetic maps.

Within the Ajdabiya Trough, the positive gravity anomalies presumably caused by multiple mantle intrusions which may have been initiated as a result of weakening of the crust under extensional forces associated with the Sirt Basin rifting events. We assumed a density of 2.98 g/cc shown in the model intended to represent a homogenous unit of intruded material that is now anomalously denser than the adjacent crust; instead, it should be taken to represent the average properties of a region rock volume containing of high density igneous intrusions. However, this high density also facilitates meaningful analysis of lower crustal structures and intra-sedimentary volcanics (e.g. Makris, and Yegorova, 2006; Casten and Snopek, 2006; Busrewil et al., 2008; Witte, 2008).

The shape of the hypothesised high-density intrusions is open to considerable modification because of ambiguities in modelling the gravity data. However gravity minima are mainly related to the marginal clastic-rock-filled basin depocentres. Thus, it follows that the minima at least partly reflect the broad gravity anomaly caused by an increased depth to Moho along the axis of the rift flanks. The Moho is deeper below the rift flanks simply due to a smaller stretching factor.

The model created by GM-SYS extends to a crustal depth of about 40 km, and therefore the whole Ajdabiya Trough crustal structure can be modelled.

To accurately model the upper crustal, residual components requires accurate definition of the regional, lower crustal density variations, such as Moho relief. Positive gravity anomalies are normally assumed to be caused by mass excess located at depth. In some cases, the positive regional gravity response from extended crust, giving rise to an elevated Moho, can be relatively well constrained from the gravity profile itself. However, gravity models are not unique and it is not possible to unequivocally determine the cause of a gravity anomaly in full extent.

The modelled profile in this study was chosen so as to traverse the major structural features in the area such as fault boundaries, structural highs and lows.

One geological profile has been modelled across the study area using well, gravity and magnetic data as a constraint. The location of the model is shown on figure10, and the model is shown at a horizontal scale of 1:1,000,000 and a vertical scale of 1:500,000.The geological cross-section is shown in the lower window and the gravity and magnetic response of the geological model andthe corresponding observed Bouguer gravity and observed magnetic intensity is shown in the upper window. The gravity and magnetic modelling also constrained by the high seismic confidence areas (Figure 4) for a better interpretation using the gravity and magnetic modelling results. A zone with no seismic penetration occurs below the basement level at approximately 6ms.Above this depth, the section is characterized by high reflective and coherent reflections. The modelling of the gravity and magnetic data is particularly aimed to extend the interpretation below the effective level of seismic penetration.

The depth information in the model was constrained by depths obtained from formation tops in well (A1-119) near the centre of the trough.

Once basin structure was determined, densities were altered in order to fit the observed gravity anomaly. We found that the geometry of the lower crust-mantle boundary (Moho) – which is not well-constrained by either borehole data or seismic reflection profiles – also had to be varied to fit the observed gravity response. The sediment densities used in the modelling are outlined summarized in Table 1. These density values for sedimentary rocks are mainly based on analysis of well logs (density and sonic) and core sample analysis from the Sirt basin (e.g, Essed, 1978). The density contrast was constructed by assuming a constant basement density of 2.67g/cc and subtracting mean sedimentary densities as used in the 2D gravity modelling. In the same context, assemblages of Ordovician, Silurian, and Devonian strata have been recovered and studied from Palaeozoic successions in wells from east Sirt Basin for the purposes of extracting real densities (Woollam and Pearce 2006).

**Table 1:** Density values of the main rock complexes (used for the gravimetric modelling of the cross-sections along the profiles 1, 2 and 3)

Main data sources: The sediment densities were estimated based on published values and previous models, published values are mainly based on analysis of well logs (density and sonic) and core sample analysis from the Sirt, Ghadames, Murzuk, Jefara and Cyrenaica areas (Essad, 1978), (Libyan Gravity Compilation Project, 2001,Makris, and Yegorova, 2006, Casten and Snopek, 2006).

| *Rock Complex* | *Density [g.cm³]* |
|---|---|
| Mid Eocene and Younger | 2.35 |
| Lower Eocene | 2.4 |
| Paleocene | 2.4 |
| Upper Cretaceous | 2.5 |
| Lower Cretaceous | 2.5 |
| Nubian | 2.54 |
| Carboniferous | 2.55 |
| Devonian | 2.55 |
| Silurian | 2.6 |
| Gergaf (Quartzitic sandstone) | 2.74 |
| Igneous | 2.91 |
| Upper Crust | 2.74 |
| Lower Crust | 2.84 |
| Mantle | 3.2 |

Analysis of the magnetic data showed that most of the magnetic signal arises from within the basement, and trends seen in the magnetic data can therefore be assumed to be basement related. A set of clear magnetic and gravity responses from the basement and the overlying sedimentary section have been traced on the produced maps. The NW-SE trending, high magnetic anomalies at the middle of the trough may be attributed to the presence of basaltic intrusions. Well A1-119 located at the central part of the Ajdabiya Trough cut Cretaceous granitic basement at 4.3 km depth in a zone with gravity and magnetic high (Hallett and El Goule 1999). This magnetic and gravity high is possibly affected by local uplifting during the Cenozoic time (Hallett, 2002). Hallett and El Goule, 1999 suggested the presence of ridge structure in this part. The magnetic map (Figure 7) shows a northwest-striking magnetic high that extends across the Amal Platform to the east. It seems to be that the northeast edge of this anomaly, caused by ultramafic volcanic rocks, coincides with a major fault zone in the area as discussed by Anketell, (1996). The coincidence of the identified fault zone and significant gravity gradients could also suggest that the much younger fault zone has reactivated older basement features. However, it is also possible that a younger fault could give rise to significant structural expression within the basement.

The 2D model (Figure 10) has been broken up into 8 layers representing (from thetop down)

1. Late Oligocene – Miocene Unite
2. Eocene – Early Oligocene Unite
3. Paleocene Unite
4. Mesozoic Unite
5. Unites between basement and base of the Mesozoic – (Camberian / Ordovician)
6. Upper Crust
7. Lower Crust
8. Mantle

The forward model was calculated using variable susceptibilities (0.0001 – 0.002 SI units) for the Paleozoic basement. These susceptibilities were chosen as a first guess to fit the major anomaly trending NW-SE associated with the significant structural elements and the main fault system in the area. The magnetic content inferred with the susceptibilities would be consistent with a fairly metamorphic and igneous lithology.

The basement fill model represents an attempt to fit the observed anomaly by changing the susceptibilities within the basement and the deeper section (Upper and lower crust unites) (Figure 10). This was done with a manual fitting to try and maintain the basic structural picture. For the most part faults were kept in the same locations and minimal change was applied to the layers to obtain this fit. The model utilizes a very low susceptibility (0.0 – 0.0008 SI unites) much lower in the column to fit the shorter wavelength anomalies on the south-eastern side of the section.

This susceptibility is consistent with those measured in metamorphic rocks (e.g. Clark and Emerson, 1991). As such, it may be showing different lateral variations in the chemical composition (lithology) or subtle structural variations and thicknesses within the basement unit. The changes made to the model occur approximately around the Paleozoic – Mesozoic boundary.

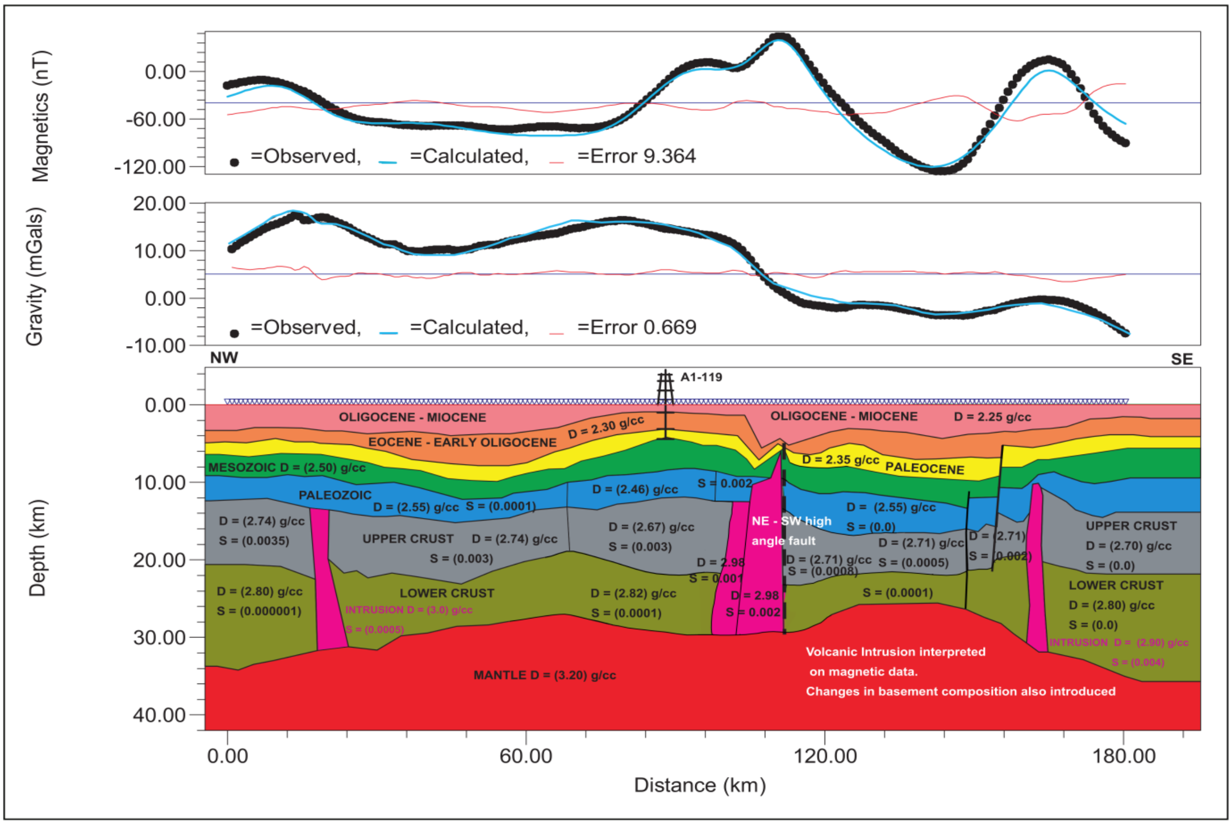


**Figure 10:** NW – SE gravity and magnetic (AA") model from central Ajdabiya Trough. The modelled gravity and magnetic anomalies are shown with unconstrained intrusive bodies. In general the volcanic activities in Libya are believed to have been concurrent with movements along deep-seated fractures perhaps in connection with the .great orogenic pulse of the Alpine cycle (Goudarzi, 1959). Crustal thickness varies under Ajdabiya Trough indicating stretching and undulations formed due to sediment loading and subsidence. Densities in g/cm3 are adopted from different sources (Libyan Gravity Compilation Project, 2001, Makris, and Yegorova, 2006, Casten and Snopek, 2006'). Published values are mainly based on analysis of well logs (density and sonic) and core sample analysis from the Sirt, Ghadames, Murzuk, Jefara and Cyrenaica areas (Essed, 1978), magnetic susceptibilities are given parenthetically with some constrains from local and regional studies.

The string of NE-SW anomalies shown on the gravity and magnetic maps are correlates with a high angle normal fault shown in the basement (Figure 10). From a magnetic point of view, these anomalies might be explained by rock deformation related to fault reactivation. The high angle fault zone is recognized on the basis of lack of seismic reflectivity. This type of structural feature possibly represents basement discontinuities that could conceivably be reactivated during the Phanerozoic (Vail, 1991).

This conclusion arises from the alternating positive and negative source susceptibility values needed to accommodate the observed anomalies.

The sharp rise in the magnetic field to the north is undoubtedly owing to the large magnetic anomaly south of the study area. Even though we are seeing the effect in the magnetic field, the major bulk of the magnetic source lies at the centre of the study area.

## 6. Discussions and Conclusions

The paper presented an integrated potential field dataset including Bouguer gravity, and combined draped satellite and aeromagnetic data that shed new light on the nature of Mesozoic - Cenozoic tectonic and crustal structure within the Ajdabiya Trough area. A combination of digital enhanced gravity and magnetic maps, coupled with joint 2D magnetic and gravity model, used to map the subsurface geology and deeper crustal structure of the region.

Specifically, I interpreted the data to compile an enhanced structure maps portraying the subsurface extent of Palaeozoic basement, Mesozoic and Cenozoic sedimentary infill and faults. The structural interpretation, based on the analysis of gravity and magnetic patterns and lineation's, reveals faults, igneous intrusions, and other structural elements.

The 2D gravity and magnetic modelling provide better constrained mapping to the tectonic and crustal structures of the Ajdabiya Trough area. The result of the modelling provided a good fit to the observed and calculated gravity and magnetic anomalies. The uncertainty errors in the modelling fits were approximately 0.5 - 2 % for the gravity data and about 10 - 48% for the magnetic data. Regarding the magnetic data, the high error in the fitting was due to the strict constraints imposed on the magnetic model which include the reduced number and geometries of magnetic sources in addition to their physical properties (magnetic susceptibilities of the sediments and the bed rocks). However, these limitations were necessary to relate each causative body with prior information from independent geological and geophysical studies. Further studies concerning the magnetic heterogeneity of the basement rocks are necessary to geologically constrain the joint modelling and to minimize the large misfit in magnetic properties. The results of the gravity and magnetic mapping and modelling indicated that the complex structural characteristics of the Ajdabiya Trough region is closely correlated with tectonic activities of the eastern Sirt Basin and Cyrenaica Platform to the east (e.g. El Arnauti et al., 2008).Since the late Palaeozoic to Early Mesozoic and during the early Cenozoic periods, the Ajdabiya Trough region was intensely deformed due to rifting episodes and extension periods that caused thickening of the upper crust and thinning of the lower crust.

According to our study of Bouguer gravity and magnetic fields and the whole crustal structure, we can bring a comprehensive tectonic model of the Ajdabiya Trough region, which can reveal the tectonic and geodynamic settings of this region, and decipher different active faults.The low Bouguer gravity was discussed earlier as being the result of crustal thickening. It might also be partly the result of lower density, granite dominated Precambrian basement indicated by the relatively low magnetic signal.

The system of the Ajdabiya Trough has been deformed by medium to high-angle extensional faults which cut down to the middle crust (Baird et al., 1996).NE-SW trends indicate wrenching or shear zones that cut the study area and extended to the Cyrenaica Platform (e.g. Anketell, 1996: El Arnauti et al., 2008).

Along the same zone, we noticed a major north south-trending strike-slip fault set. It is possibly inked to very deep source as deformation and possible strain partitioning in the lower crust and the upper mantle was distributed over a broad region of the eastern Ajdabiya Trough and over Cyrenaica Platform (El Arnauti et al., 2008).

Associated fold structures were recognized also near the Cyrenaica region on horizontal gradient maps. This could be related to inversion tectonics occurred during the Santonian time(ca. 84 - 87 Ma)(e.g. Ziegler et al., 2001; Anketell et al., 1996; El Arnauti et al., 2008). NW-SE trending structures are predominant, along with subordinate of E-W trending features, parallel to structures formed during rifting stages (e.g. Baird et al., 1996; Ahlbrandt, 2001; El Arnauti et al., 2008), in addition to N-S, and NE-SW trends possibly inherited from Pan-African orogeny and Late Palaeozoic deformations.The mapped gravity highs in the Ajdabiya Trough area and northern Cyrenaica may be also associated with fundamentals of WNW-ESE strike-slip faulting(Figures 8 and 9), in response to transpressional tectonics (e.g. Anketell, 1996; El Arnauti et al., 2008).

This high area possibly continues offshore and could therefore be part of a large feature involving uplift and northward, development of oceanic crust.

It has been suggested that an impressive African rift system which started in the early to late Cretaceous has its roots deep in the Pan African N-S and E-W trends (Ziegler et al., 1999; Maurin and Guirand, 1993). At shallow levels (ca. <0.5 km), short wave length and high frequency anomalies are interpreted to be a fault and fold structures and mainly die out into the deeper strata. A possible geological interpretation is that the earliest structures developed along the E-W trend during the early Cretaceous, possibly in response to extension along the edge of the Neo-Tethys, resulting in the development of E-W troughs and highs across the northern part of Libya (Bosworth et al., 2008).

The African plate was subducted underneath the Eurasian plate during the tectonic interactions between the two plates (e.g. Capitanio et al., 2009). This affected major part from Sirt Basin including the northern part of the Ajdabiya Trough which was subsequently affected by NE-SW crustal extension due to the bending of the continental crust of the African Plate formed NW-SE trending structures in the northern part of the Ajdabyia Trough and give way to a high dense material from the mantle to be in shallow depths as recognized from the gravity and the magnetic model. This subsequently followed by thinning of the continental crust beneath the northern part of the Ajdabyia Trough with possible subsequent emplacement of oceanic crust (e.g. Ahlbrandt, 2001). The region is also characterized by high heat flow, and mildly deformed (stretched) continental crust (e.g.Burwood et al., 2003; El Arnauti et al., 2008).The gravity and magnetic model show a strong regional trend as the central area is approached. This is interpreted as due to a dramatic crustal thinning and rise of the Moho from around 35 km depth at profile ends to about26 km depth at the centre. Thickness of the lower crust increases with tectonic age, implying lower crustal growth with time by tectonic subsidence (Holt et al., 2012).

The NE-SW tectonic extension within the northern part of the Ajdabiya Trough is more recent than southern parts, which is possibly related to the late stage of formation of the Sirt Basin, during the collision between the African and Eurasian plates (McKenzie, 1970; Jackson and McKenzie, 1984a, b, 1988).

The idea is supported by independent evidence of magmatism in the Sirt Basin (Busrewil et al., 2008; Capitanio et al., 2009), it could explain the stretching during the Paleogene, although this process could possibly account for the Neogene evolution of the Sirt domains, when tilting, regional subsidence and magmatic activity took place (Ade-Hall et al., 1974; Schäfer et al., 1981; van der Meer and Cloetingh, 1993).

High angle NE-SW basement fault recognized from the magnetic and gravity maps and the model separated the northern part of the trough from the southern part. It seems to be that the southern part of the trough is dominated by NE-SW trending fault system of the same generation and possibly inherited Hercynian reactivated faults. The analysis shows that a modern, high-resolution aeromagnetic survey is needed to confirm these interpretations.

Lineaments sub-parallel, oblique, and sub-perpendicular to the Ajdabiya Trough structural domain are interpreted from the Bouguer gravity data. In Cyrenaica region to the east lineaments generally correspond to mapped thrusts and/or terrane boundaries (e.g. Gumati and Nairn, 1991; Gumati et al., 1996;Anketell et al., 1996; El Arnauti et al., 2008).

Lineaments that do not correspond to mapped thrusts may represent structures in Pan-African and post Hercynian basement created as normal faults during Mesozoic rifting. We show that these features reflect faults in crustal basement formed and reactivated during periods of the Mesozoic rifting. Normal and strike slip faults formed during the Mesozoic rifting may have reactivated during subduction and Late Cretaceous rifting at about ca. 60 Ma.

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## Author Profile

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