Petroleum Res. J. Vol. 20 (2007); P. 45–58, 7 Figs.

Integration of Remote Sensing and Geophysical Data: A Case Study of Structural Development and Petroleum Prospectivety of Western Sirt Basin, Libya

Khalifa M. Abdunaser and Giuma Reeh*

دمج معلومات الاستشعار عن بعد والمعلومات الجيوفزيائية: دراسة حالة تطور تكتوني واحتمالات نفطية بمنطقة غرب حوض سرت، ليبيا

خليفة عبد الناصر وجمعة ريح

تم في هذه الدراسة تحليل صور الأقمار الصناعية وتفسير المعلومات الرادارية والجيوفزيائية وبعض سرود الآبار للتعرف على التراكيب الجيولوجية لمنطقة شمال غربي حوض سرت.

إن استعمال التحليل البصري والرقمي لصور الأقمار الصناعية ساعد في تخريط الظواهر والتراكيب التكتونية الإقليمية وعند دمجها مع المعلومات الرادارية تم الحصول على معلومات إضافية أخرى أكثر تفصيلاً. معلومات الجاذبية والمسح المغناطيسي الجوي التي خضعت إلى العديد من التحليل الترددي وتحويل فورير والمصفيات والتحسين الرقمي (المشتقة الرأسية الأولى، الممال الأفقي والكلي) أوضحت أن بعض الشاذات ذات أعماق وأحجام مختلفة.

توجد علاقة قوية بين التكاوين الجيولوجية السطحية والتحت سطحية، وساعدت المعلومات السيزمية في تحديد أعمار وتطور الصدوع. تم توحيد المعلومات السيزمية والجيوفزيائية الأخرى مع تفسير المعلومات الرقمية للأقمار الصناعية باستخدام منظومة المعالجة الرقمية (ER Mapper Software) ووضعها على هيئة طبقات باستخدام منظومة المعلومات الجغرافية (ArcGIS).

تمتاز منطقة الدراسة بتواجد كثيف للتراكيب الجيولوجية ذات الاتجاه شمال شمال غرب إلى جنوب جنوب شرق متعامدة مع تراكيب جيولوجية اقل وضوحاً تأخذ الاتجاه شرق شمال شرق إلى غرب جنوب غرب ويعتقد إنها الأحدث عمراً والتي يحتمل تأثرها باتجاه الحركة الهرسينية التي تتوافق مع التراكيب الجيولوجية الإقليمية لمنطقة غربي حوض سرت.

تم تحديد بعض المجاميع التركيبية والمعالم الاستكشافية المرشدة بناءاً على تواجد التراكيب الجيولوجية السطحية التي تظهر على صور الأقمار الصناعية والتي تتوافق مع التراكيب الجيولوجية التحت سطحية التي تم تحديدها بواسطة المعلومات الجيوفزيائية. ويعتقد إن المعالم التركيبية المرشدة هي مصائد تركيبية كما تظهر على صور الأقمار الصناعية والتي تم تحديدها بناءاً على وجه التشابه مع التراكيب الجيولوجية للحقول النفطية المكتشفة بالمنطقة.

Abstract: *Satellite image analysis, radar data interpretation, gravity, magnetic data available seismic reflection profiles and well logs, have been used to define the geological structure of the northwestern portion of the Sirt Basin, Libya.*

Visual and digital satellite image analysis have enabled, rapid mapping of the regional tectonic structures and features while when merged with radar revealed additional and more detailed information. The gravity and the aeromagnetic data were subjected to several analytical and FFT frequency-based analyses, filtering and image enhancements including first vertical derivative, horizontal gradient and analytic signal have

* Libyan Petroleum Institute, P O Box: 6431, Tripoli-Libya.

showed anomalies from sources of various size and depth.

They established a good relationship between the surface and subsurface structure, such as the identification of basement structure while integration of regional seismic lines helped to establish the structural and timing of fault development. The representative seismic lines and regional Potential Fields data have been co-registered and scaled to fit the digital satellite image interpretation maps using ER MAPPER and ArcGIS software. The study area is characterised by a strong NNW-SSE structural grain with less ENE-WSW trending structures that appear to be superimposed on the NNW-SSE structures. The later trend may be influenced by pre-existing Hercynian structure, which is consistent with the regional structure of the western Sirt Basin.

A number of structural domains and exploration leads were identified based on the surface structures expressed on satellite imagery, and generally, show good correlation with regional subsurface structural features defined by seismic and potential fields data. The leads are primarily structural traps with a related surface expression as interpreted from the data used. The structural setting of existing oil fields in the region were used as analogues for assessing the exploration potential of the surface structures.

INTRODUCTION

The study covers the western Sirt Basin, Libya (Fig. 1). It has been undertaken jointly by the Libyan Petroleum Institute, Infoterra and Teknica and is part of a larger programme to investigate the geology and hydrocarbon evaluation of Tertiary and Mesozoic rocks of the Western Sirt Basin of Libya. The main objective of this study is to delineate the geological structure of northwestern Sirt Basin.

Methodolgy

The study involved the following:

1. Acquisition and processing of 13 scenes of Landsat TM and 31 scenes of ERS SAR

• The Landsat TM and ERS data were digitally enhanced.

• Landsat TM Bands 7,4,2 were selected and displayed as red, green, and blue *(RGB);*

2. Generation of a merged Landsat TM/ERS SAR satellite image mosaic;

3. Structural geological interpretation of Landsat TM and ERS SAR satellite imagery;

4. Gravity and Aeromagnetic data were subjected to several analytical and FFT frequency-based analyses, filtering and image enhancements including first vertical derivative, horizontal gradient and analytic signal;

5. Integration of subsurface structure derived

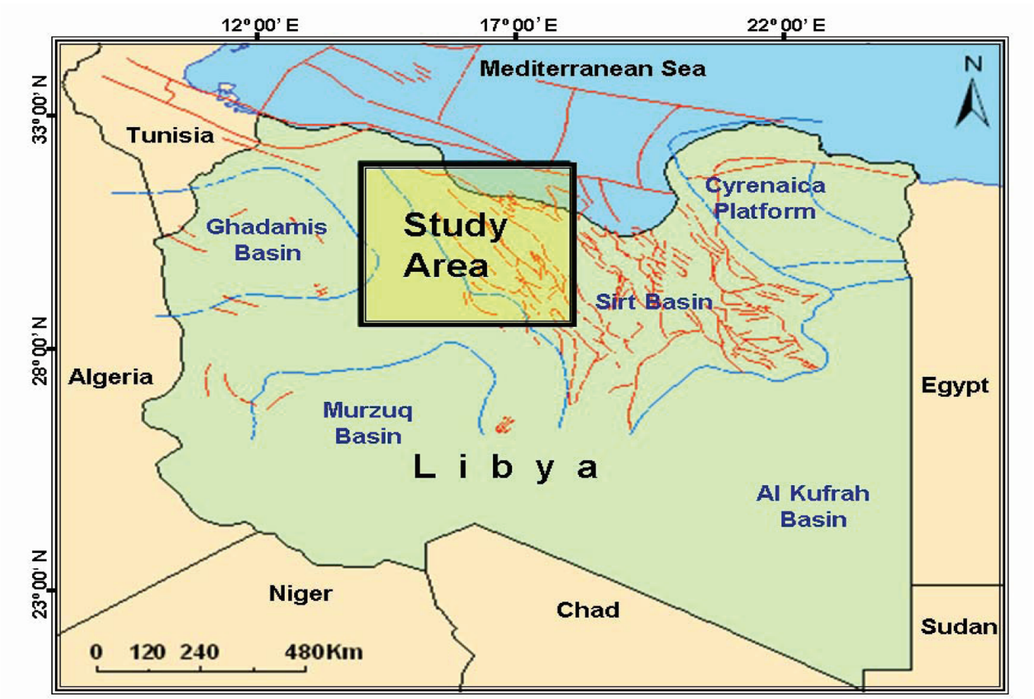

Fig. 1. Location map of western Sirt Basin study area.

from interpreted seismic profile, well correlations, oil fields and potential field data.

Geological interpretation was performed digitally on-screen using ArcGIS software, scales ranging from 1:100,000 – 1:250,000, and hardcopy satellite imagery at a 1:250,000 scale and a 1:500,000 scale was used to provide a 'regional' context during the on-screen geological interpretation.

TECTONICS

The Sirt Basin is the youngest and the greatest petroleum-bearing basin in Libya. The eastern half of the study area has been extensively surveyed for its oil exploration during the past century. The evolutionary history of the Sirt Basin is complex and marked by at least two main tectonic events (Ahlbrandt, 2001; and El-Batroukh and Zentani, 1980); namely the Hercynian Orogeny at the end of Palaeozoic time and the extensional "rifting" event in Pre-Cretaceous to Paleogene time.

The Hercynian Orogeny led to the formation of the entire basin and to the creation of northeast-southwest structural trends. The Pre-Cretacous to Paleogene rifting event led to the generation of a series of northwest-southeast oriented grabens and horsts bounded by deep-seated normal faults that step progressively downward to the east in the basin. Block faulting is the common tectonic style in the Sirt Basin.

The complex tectonic history of the Sirt Basin resulted in the formation of multiple reservoirs and conditions that favored hydrocarbon generation, migration, and accumulation, principally on or adjacent to the horst blocks (Ahlbrandt, 2001). Carbonate reservoirs, mostly of Palaeocene and Eocene age, are also concentrated on the structural highs in the central Sirt Basin (e.g. Az Zahrah Platform). These reservoirs were in turn charged by vertical migration along faults during the peak of petroleum generation period of the early Tertiary.

STRATIGRAPHY

The surface stratigraphy of the western Sirt Basin (Fig. 2) is dominated by sedimentary rocks ranging in age from Late Cretaceous to Tertiary with the exception of scattered Precambrian and Cambro-Ordovician outcrop of the Al Qarqaf Arch in the southwest.

STRUCTURAL GEOLOGICAL INTERPRETATION OF THE SATELLITE IMAGERY

Hun Graben

The Hun Graben is a present-day fault bounded basin 305km long, and 33.5-48km wide (Fig. 3). The graben trends NNW-SSE, although its southern end changes to E-W and links with the Zallah Trough and is infilled mainly by Oligocene Mazul Ninah Formation.

The Hun Graben appears to cross-cut existing northeast draining wadi channels (Fig. 3). Along the western margin of the basin, wadis generally narrow and become incised as they approach the margin of the graben, indicating that they have been rejuvenated by the formation of the graben. The northeast draining channel is deflected as it enters the Hun Graben suggesting that it was possibly modified by development of the Hun Graben in the Oligocene time.

A number of open folds have been interpreted within Mazul Ninah Formation along the margins of the graben. The folds have probably formed in response to drag in the hanging wall to the basin bounding faults or possibly due to roll-over or non-planar fault trajectories in the subsurface. Lava flows of Jabal As Sawda in the SW of the area appear to post-date the N-S trending faults.

Waddan Uplift

This uplift is a gentle NNE tilted block narrowing in the north before it disappears below the coastal plain. It is a convex to the south, bounded by fault with downthrow to the SW, S and SE. The common trend is ENE-WSW, then NNW-SSW to NW-SE. N-S and E-W trending faults are also developed.

The northern half of the uplift is characterised by north and north-northeast dendritic drainage down the sub-horizontal dip slope of the structure. A more organised trellis drainage pattern has developed towards the northern end of the structure parallel to the NNW-SSE and ENE-WSW trending fracture system. Elongated erosional escarpments of more resistant lithologies and/or fault scarps may also control linear NNW-SSE trending wadi channels (Fig. 3). The NNE dip slope is also cross-cut by a N-S trending minor fault system which appears to be the onshore extension of an offshore fault trend. The SE part of the Waddan Uplift appears to be associated

Era	Period		Epoch	Unit Name	Lithology
Cenozoic	Quaternary		Recent	Fluvio-eolian and recent wadi deposits	Fluvio-eolian and recent wadi deposits
			Holocene	Sabkha deposits	Sabkha deposits
			Pleistocene	Ancient wadi terraces	Ancient wadi terraces
	Tertiary	Pliocene	Pleistocene	Al Hishah Fm.	Fine gypsiferous marl, calcarenite, and sandy clay
		Miocene	Langhian	Al Khums Fm.	Limestone, many limestone and calcarenite
		Oligocene	Chattian	Upper Member of Mazul Ninah Fm.	Gypsum manly limestone
			Rupelian	Lower Member of Mazul Ninah Fm.	Gypsum, marl sandy limestone
		Eocene	Lutetian-Priabonian	Wadi Thamat Fm.	Marl, limesone and dolomitic limestone
			Ypresian-Lutetian	Al Jir Fm.	Chalky to manly dolomite and dolomitic limestone
			Thanetian-Ypresian	Bishima Fm.	Gypsiferous marl to manistone, dolomite, chalky dolomite and limestone
		Palaeocene	Thanetian	Shurfah Fm.	Limestone, marl, many limestone, calcarenite and calcilutite
			Danian	Upper Member of Zimam Fm.	Calcenous dolomite to dolomitic limestone
Mesozoic	Cretaceous		Maastrichtian	Lower Member of Zimam Fm.	Marl, marly limestone
			Campanian	Mizdah Fm.	Limestone, marly limestone and gypsiferous
			Turonian-Coniacian	Qasr Tigrinnah Fm.	Limestone, manly limestone, sandstones, and gypsum and clay
Palaeozoic			Cambrian	Al Hassaouna Fm.	Conglomeratic sandstone
Precambrian			Precambrian	Basement	Basement

Fig. 2. Generalized str0atigraphy of the study area (After Mijalkovic, N. 1977, Said, M. 1981, and Zivanovic, M. 1977).

with a downthrown fault block, which is defined by a broad low amplitude anticlinal structure that developed in Wadi Thamat Formation.

Zallah Trough

The limits of Zallah Trough are well defined at the surface and the SW margin is bounded by a north downthrowing, normal fault zone. Large triangular bedding facets or flat-irons indicate E dipping strata into the trough along the eastern end of the Al Qarqaf Arch.

The structure of the Zallah Trough is characterised by an increased intensity of faults and fault related folds (drag-folds which are typically narrow asymmetric monoclinal structures). Larger very low amplitude, periclinal folds with four-way closure and shallow plunge are also present (Figs. 3 and 4).

Elongated asymmetric synclines associated with shallow west limbs and steeper dipping east limbs

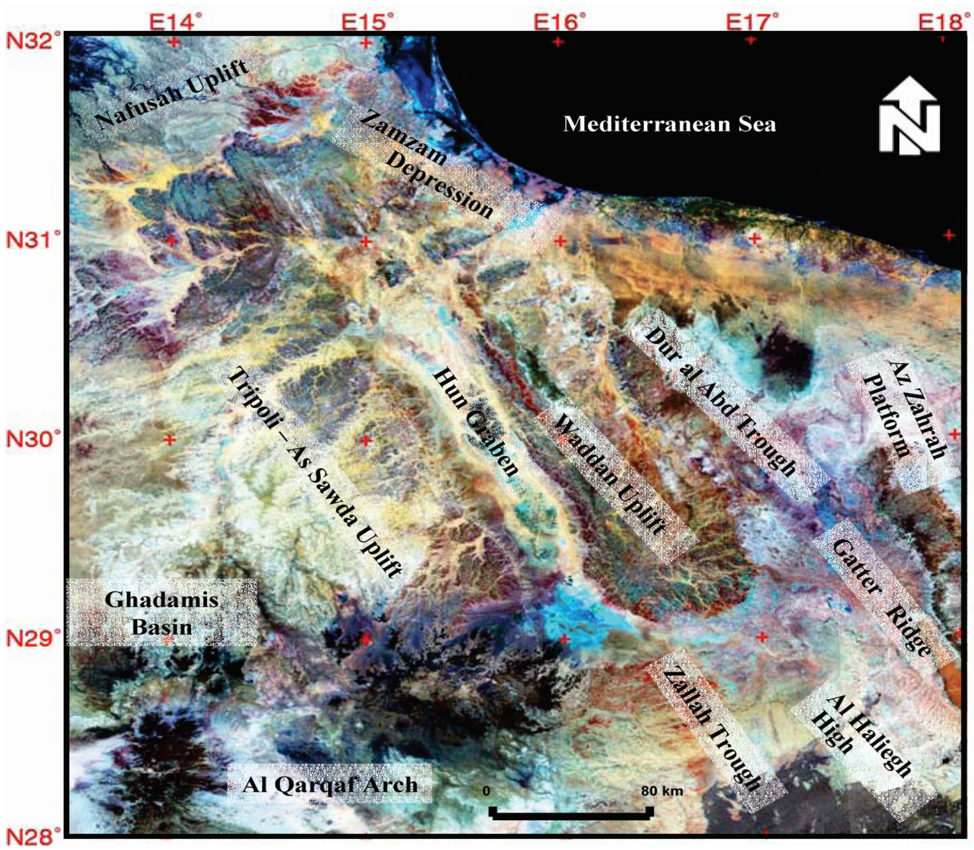

Fig. 3. Landsat 5 TM image bands 7, 4 , 2 displayed as red, green, and blue *(RGB)* shows the main interpreted structural elements of the study area.

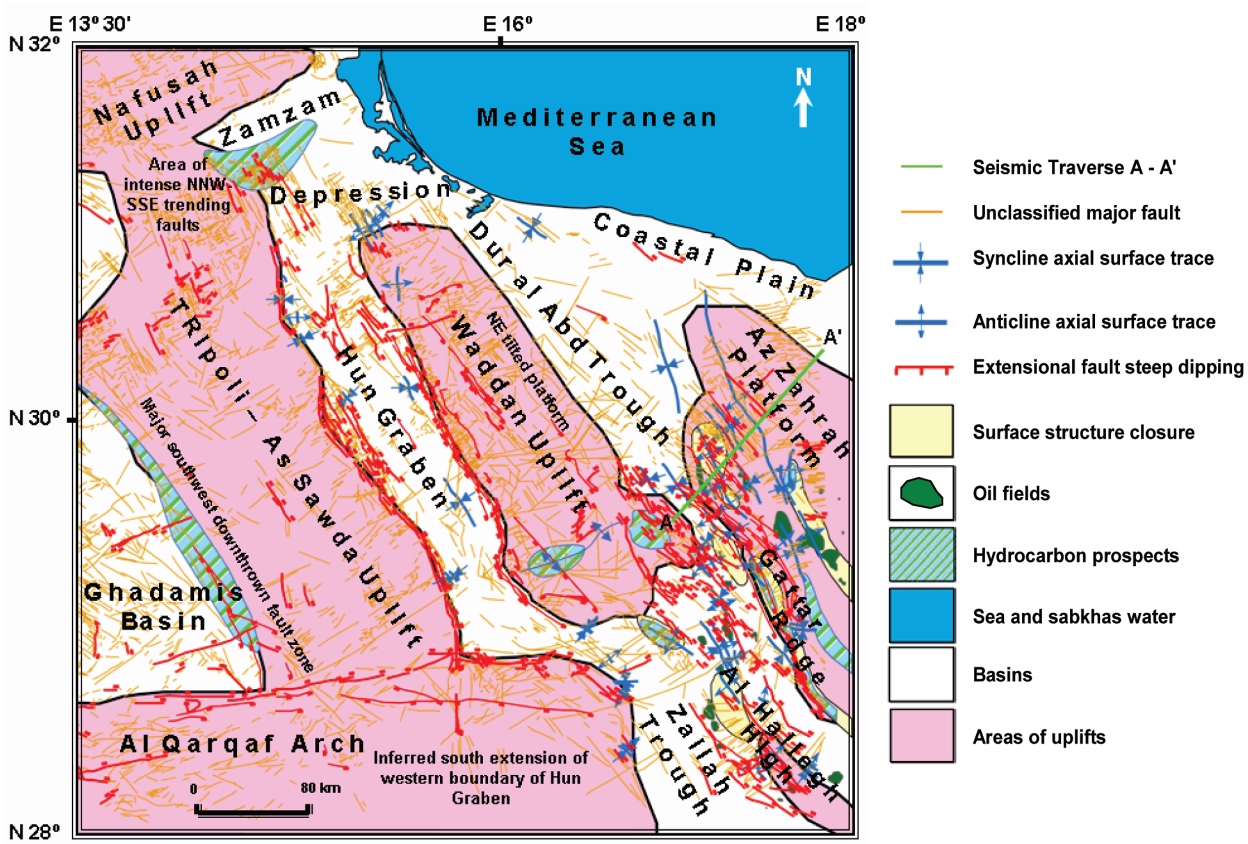

Fig. 4. Structural overview map based on satellite image interpretation.

are developed in the hanging wall and adjacent to west down throwing normal faults. The eastern margin of Zallah Trough is marked by a series of major fault scarps which coincide with a normal fault zone defining the western edge of the Gattar Ridge and Az Zahrah Platform. The preservation of Oligocene sediments is suggestive of subsidence at Late Tertiary-Quaternary times.

The Zallah Trough contains a number of subtle low amplitude periclinal structures which are exposed at surface. Most of these surface structures are associated with the following producing oil fields (Fig. 4).

Karim Oil Field:- It is a NNW-SSE trending periclinal structure expressed at surface in Mazul Ninah and Al Khums formations. It has a gentle plunge to the SSE and may be structurally closed at its northern end by NE-SW trending transverse faults associated with normal displacement. Many NW-SE trending normal faults intersect the structure with a downthrow dominantly to the southwest.

The main axis of the structure is 38km long and its width is 24.5km at surface. It is separated from the Aswad and Zallah oil fields to the north by a narrow NE-SW trending basaltic lava flow that occupies a topographically inverted palaeodrainage system.

Aswad and Zallah Oil Fields:- They are associated with a large subtle domal structure, 27km long by 22.5km wide expressed at surface within Mazul Ninah and Al Khums formations. The Mazul Ninah Formation is exposed in the erosional core of the structure. The fold structure is bounded by a NNW-SSE trending fault on its eastern side with down throw to the west and a similar trending normal faults are occur near the crest of the structure.

Hakim and Fidda Oil Fields:- These oil fields are associated with a narrow NNW-SSE trending surface anticline expressed in Al Khums Formation and Late Tertiary-Quaternary sediments. The anticline is closely associated with faults which are oblique to the main fold structure and are splays to a major fault zone to the east (Fig. 4). The structure is approximately 36.5km long and 4km wide.

Mellugh, Ghani and Zenab Oil Fields:- These fields are located in the vicinity of a NNW-SSE to NW-SE trending arcuate fault zone associated with normal downthrow to the west (Figs. 3 and 4). Localised folds are developed within the fault zone.

Daba, Gsur, Tagrifet and Facha Oil Fields:- They are situated on a NNW-SSE trend north of a synclinal area on the hanging wall side of the boundary fault of the Gattar Ridge. Faults in the vicinity of the fields downthrow to the northeast along strike continuation of the eastern boundary faults of the Waddan Uplift.

Al Haleigh High

The Al Haleigh High is a NNW-SSE trending narrow basement ridge or horst block which protrudes into the southern part of the Zallah Trough (Fig. 4). The surface structure appears to suggest that there is a lateral continuation of this feature northwards to the southern edge of the Waddan Uplift. The Hakim and Fidda oil fields are on strike with the Al Haleigh High, while two broad, low amplitude periclines at surface may be related to the reactivation of faults bounding the Al Haleigh High. The fields are represented at the surface by periclines developed mainly in Wadi Thamat Formation.

Dur al Abd Trough

It forms the northern extension of the Zallah Trough and primarily follows the NNW-SSE trending structural grain of the region. The transition between the Zallah and Dur al Abd Trough coincides with the northern end of the Gattar Ridge, close to the location of the ENE-WSW trending transverse zone. Dur al Abd Trough contains two main fault trends:

- NNW-SSE dominant fault trend of the Sirt Basin, associated with a subsidiary later ENE-WSW transverse fault set;
- N-S trending faults which become evident on the northeastern dipping flank of the Waddan Uplift and extend into the Dur al Abd Trough. These faults represent a new fault trend and may indicate the presence of a different structural regime offshore.

Gattar Ridge

The Gattar Ridge is coincident with a 15km wide, 120km long NNW-SSE trending northeast tilted panel of Al Jir Formation at surface. The western edge of the fault block is bounded by a fault zone up to 1km wide, consisting of overlapping parallel normal faults consistently down throwing to the west.

It is also associated with horsetail splay faults which may indicate a component of sinistral strike-slip. The panel is bounded to the north-northwest by an ENE-WSW trending transverse fault. To the north-northwest, the Gattar Ridge dies out into an area of close spaced faults with NW-SE trend. The faults cross-cut Wadi Thamat Formation, Upper and Lower Members of the Mazul Ninah Formation and Late Tertiary-Quaternary deposits. The dominant fault trend is NNW-SSE (Fig. 4) and subsidiary E-W and NE-SW faults sets are also developed.

Az Zahrah Platform

The northern end of the Az Zahrah Platform (Fig. 4) is expressed at surface in the north by a homoclinal shallow NE dipping and marked by a NNW plunging nose of a large low-amplitude anticline. It is cross-cut by a 15-20km wide NE-SW trending fault zone while the dominant fault trend is NNW-SSE. Many NNW-SSE trending low amplitude gentle flexures are expressed by erosional features and surface geomorphology. An anticlinal monoclinal fold defines the western margin of the platform. The boundaries of the fault zone are defined by:

- NE-SW trending monoclinal flexures in the bedding that provide a relative sense of downthrow across the fault zone; and
- Changes in the amount of plunge of the NNW-SSE trending fold hinges of the Az Zahrah Platform and adjacent Gattar Ridge.

Five major oil fields are located along the western crest of the Az Zahrah Platform:

Bahi Oil Field:- It is situated on the northern end of the Az Zahrah Platform, approximately 14km to the south of the NE-SW trending transverse fault zone in the erosional window developed above the structural crest of the Az Zahrah Platform, 4.5km east of the fault bounded western margin of the platform.

Dahra* Oil *field:It is situated within a NNW-SSE trending open syncline east of the monoclinal margin. NE-SW trending transverse faults occur in the area.

Jofra* Oil *Field: The field is situated to the east of the monoclinal margin in a structural position similar to the Dahra field. A significant NE-SW trending, possibly fracture controlled, erosional window is present to the north of the field.

Ali and Almas Oil Fields: The two fields are located on the gentle northeast dipping limb of the Az Zahrah Platform

Eastern Ghadamis Basin

This uplift is characterised by a gentle northeast dipping region of Tertiary strata with a relatively simple structure and well established dendritic drainage pattern. The dominant structural grain is NNW-SSE to NW-SE trending faults associated with down throw to the WSW, opposite to the drainage direction.

Towards the west, a NW-SE to WNW-ESE trending set of faults becomes evident and the fault zone is on-trend with the Pan-African Al Haruj Uplift. This feature forms the divide between the Ghadamis Basin and Zamzam Depression.

Nafusah Uplift

This is a major E-W trending topographic ridge which forms a major drainage divide in the northwestern part of the study area. The uplift is associated with the exposure of Cretaceous lithostratigraphic units in the study area. The structure is considered to be a Late Palaeozoic to Mesozoic Hercynian structure (Klitzsch, 1971; Anketell, 1996). The structure forms the northern boundary of the Ghadamis Basin. The southern margin is fault bounded at least in part in the subsurface, but this is not evident on the satellite imagery. Eocene tectonism is the primary cause for the emplacement of flood basalts. The Nafusah Uplift is associated with N-S and NE-SW trending faults (Fig. 4).

Al Qarqaf Arch

The Al Qarqaf Arch is an E-W trending Hercynian structure located on the southwestern edge of the study area and exposes Neoproterozoic basement rocks and Palaeozoic sedimentary sequences onlapped by Oligocene cover rocks. Regionally the structure forms a WSW-ENE topographic high which separates the Murzuq and Ghadamis basins. The core of the structure is formed by Jabal Hasawnah, which is elevated 800m above mean sea level.

The structural grain of the Al Qarqaf Arch is dominated by ENE-WSW trending faults and resistant ridges (possibly silicified relict fault planes and/or igneous dykes)?. Subsidiary WNW-ESE to NW-SE and N-S trending faults also occur (Fig. 4).

Tripoli-Tibisti and Al Haruj Uplifts

The Tripoli-Tibisti and Al Haruj Uplifts are subsurface Pan-African basement highs which trend NNW-SSE across the western part of the study area to the west of the Hun Graben. The actual position and effect of these structures on the surface geology and geomorphology is unclear. The Tripoli-Tibisti Uplift is coincident with the alignment of volcanic rocks emplaced during the Eocene to Recent. Reactivation of basement faults related to either of these two structures may be responsible for the location of the NNW-SSE trending, west-southwest down throwing normal fault zone (Figs. 3 and 4).

Zamzam Depression

The surface expression of the Zamzam Depression is extremely subtle on the satellite imagery (Fig. 3). The structure represents the eastern extension of the Ghadamis Basin and is overlain by the western margin of the younger Sirt Basin. The Ghadamis Basin and Zamzam Depression are 'separated' by the NNW-SSE trending Tripoli As Sawda Uplift. The Zamzam Depression may be coincident with the northward plunge of the Hun Graben. The region associated with the Zamzam Depression is dominated by NNW-SSE trending faults associated with minor normal displacement (Fig. 3). ENE-WSW trending cross-cutting faults are also developed.

A 10-15km wide ENE-WSW fault zone also transects the northern end of the Hun Graben possible indicating the southern margin of the Zamzam Depression (Fig. 4). The boundaries of the fault zone are indicated by narrow anticline and syncline monoclinal folds

SEISMIC IRETATION

The available seismic data has provided support for the interpretation and understanding of the geological history as a geologic framework that integrates the surface and subsurface geologic data with geophysical data of the western part of the Sirt Basin. The data used was compiled and processed by Teknica Company as part of a larger study on the geology and hydrocarbon evaluation of Tertiary and Mesozoic rocks of the western Sirt Basin of Libya.

This work contains an interpreted seismic traverse profile that has been composed from individual seismic lines of different vintages and different field acquisition and processing parameters. Teknica's procedure for handling line-to-line mis-ties based on different seismic datum has been incorporated into the combined traverse sections. Because there are no long lines that cross the whole study area, several shorter lines (usually of different seismic vintages) had to be combined. This sometimes resulted in data gaps and offsets between the adjoining lines.

The selected section crosses the south-eastern margin of Waddan Uplift to the south-western of the section and extends into the boundary line between Az Zahrah Platform and Maradah Trough to the north-east. It shows the location of, and difference in, structural complexity of the platforms and adjoining troughs and also helps to illustrate the major tectonic elements. The seismic section used in this study is about 225Km in length and shows two gaps, 2.8km and 7km in length (Fig. 5).

The hinge zone between the Waddan Uplift and the Dur al Abd Trough contains many (about 8) large down-to-basin faults, two of which appear to extend to the surface. Many smaller, additional faults with both down-to-basin and down-to-margin throws are believed to be present. The apparent throws of the large eight faults vary between ~ 10 and 350 ms (15 and 525 m). It has been anticipated that all of these hinge zone faults will have some lesser degree of wrench movement.

The dimensions of the Dur al Abd Trough are difficult to determine on this section, but they appear to extend from about point x1 to x2. The sedimentary section extends below the maximum time indicated on plotted seismic section (~ 3000m) and is expected to include rocks of pre-Cretaceous to Oligocene age. Within the trough, the bedding is broken by numerous down-to-basin and antithetic faults; most of which show some growth, indicating either reoccurring normal or wrench faulting in conjunction with slump faulting associated with the rapid compaction of the sedimentary column within the trough as it accumulated basin fill.

In the hinge zone between the Dur al Abd Trough and the Az Zahrah Platform a major anticline broken in places by both down-to-basin and down-to-margin faults exists and its reservoirs have been the target of a large number of Concession 17 wells (Mabruk Field). Some of the large faults of the area extend to, and have been observed cutting through, the Upper Eocene sediments that outcrop at the surface.

Generally on the Az Zahrah Platform, the Cretaceous to Oligocene sedimentary section consists

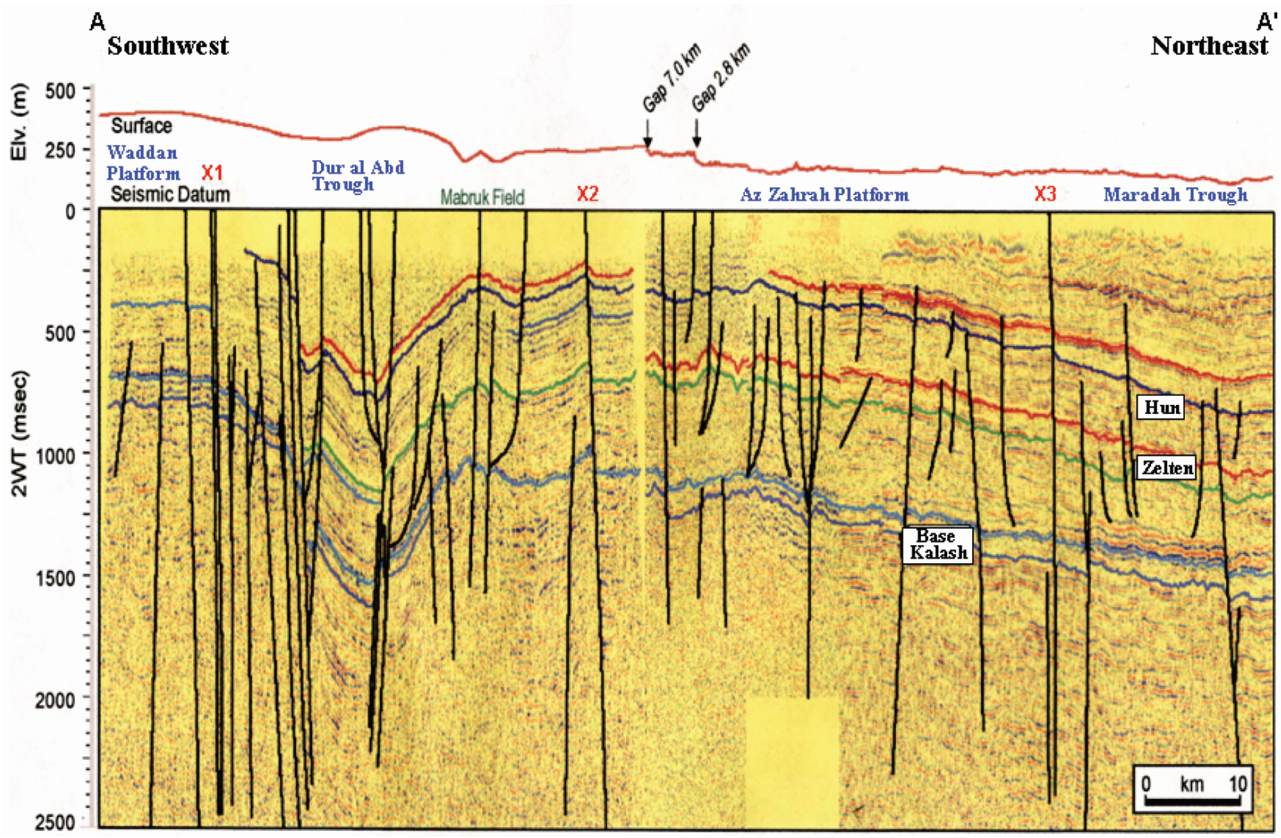

Fig. 5. A selected seismic traverse (A-A') crosses the Waddan Uplift through Dur al Abd Trough and Az Zahrah Platform to the western boundary of Maradah Trough.

of a sequence of almost parallel-bedded strata that dip gently to the northeast (at ~1-5°) and thin by ~5%. The sediments in the Az Zahrah Platform are also fractured by numerous faults, some with pop up compressional features, but the majority have the appearance of being primarily of normal (tensional) origin and may be partially of wrench tectonic origin.

Some normal faults terminate below the near base Kalash seismic time marker. Some faults that are basement rooted extend to the surface. Some faults are antithetic to basement- rooted faults. Basement-rooted faults and those antithetic to them show fault patterns similar to "flower" structures. Several of the larger Az Zahrah Platform faults that are observed on this seismic traverse extend to the surface, where they have been mapped cutting the Upper Eocene and Oligocene formations on the western margin of the platform.

The boundary between the north-eastern edge of the Az Zahrah Platform and the Maradah Trough seems to be present at point x3 close to a large NE dipping, normal fault that extends from the surface to the bottom of the seismic section. This hinge zone is only weakly deformed, being fractured by a small number of faults. The apparent throws of these faults are also small, in the range of 15-30 ms (20-45 m).

In this section, the beds of Maradah Trough dip gently to NE and became flat while the syncline axis of it is probably located to the east of the section.

GRAVITY INTERPRETATION

The gravity data were re-projected to UTM-Zone 33, WGS84 and gridded at a 1 km grid cell size. The observed gravity data were reduced to sea level using the Geodetic Reference System of 1967 (International Union of Geodesy and Geophysics, 1971) and referenced to the International Gravity Standardization Net 1971 gravity datum (Morelli *et al*., 1974).

The observed gravity data were reduced to simple Bouguer gravity with a reduction density of 2.67 g/cm^3.

- Box A. Shows a clear syncline to the north of Az Zahrah Platform.
- Box B. Is confirming the existence of a horst and graben to the southeast of Waddan Uplift.
- Box C. Reveals the clear boundaries between Zallah Trough, Al Haleigh High and Gattar Ridge.

In order to separate the long wavelength regional trend from the short wavelength residual field, a numerical technique known as trend surface analysis was applied on the Bouguer gravity grid. Removing the regional trend from the data would leave the residual field attributed to the local geological features. The residual Bouguer gravity was calculated up to three polynomial orders. In principal, increasing the order of the polynomial would lead closer approximation of the regional trend to the real data.

There is a pronounced east-west trending high Bouguer anomaly at the northwestern corner of the first order residual of the Bouguer gravity map (Fig. 6). This anomaly crosscuts the major tectonic trends in the area and appears to be due to major basement faults. This trend is probably related to the deepening of the basement towards the Mediterranean Sea to the north. The Al Qarqaf Arch is associated with a broad semi-circular high gravity anomaly. This could be associated with an uplifted basement or igneous intrusions and high topography.

There is a weak correlation between the Bouguer gravity data and the tectonic elements trends and the geological structures at some places on the map. For example, the Waddan Uplift is associated with a low gravity anomaly whereas the north-west part of Hun Graben is associated with a high gravity anomaly. A possible explanation (assuming accurate mapping of the tectonic elements) is that the gravity data is in part controlled by density variation of the sedimentary section (particularly the presence or absence of evaporites) rather than the basement.

Total-horizontal-gravity-gradient Calculation

The aim of total-horizontal-gravity-gradient calculation is to identify faults and define their distribution. A fault is reflected as a gravity gradient belt in Bouguer gravity anomaly. Total-horizontal-gravity-gradient calculation transforms gravity

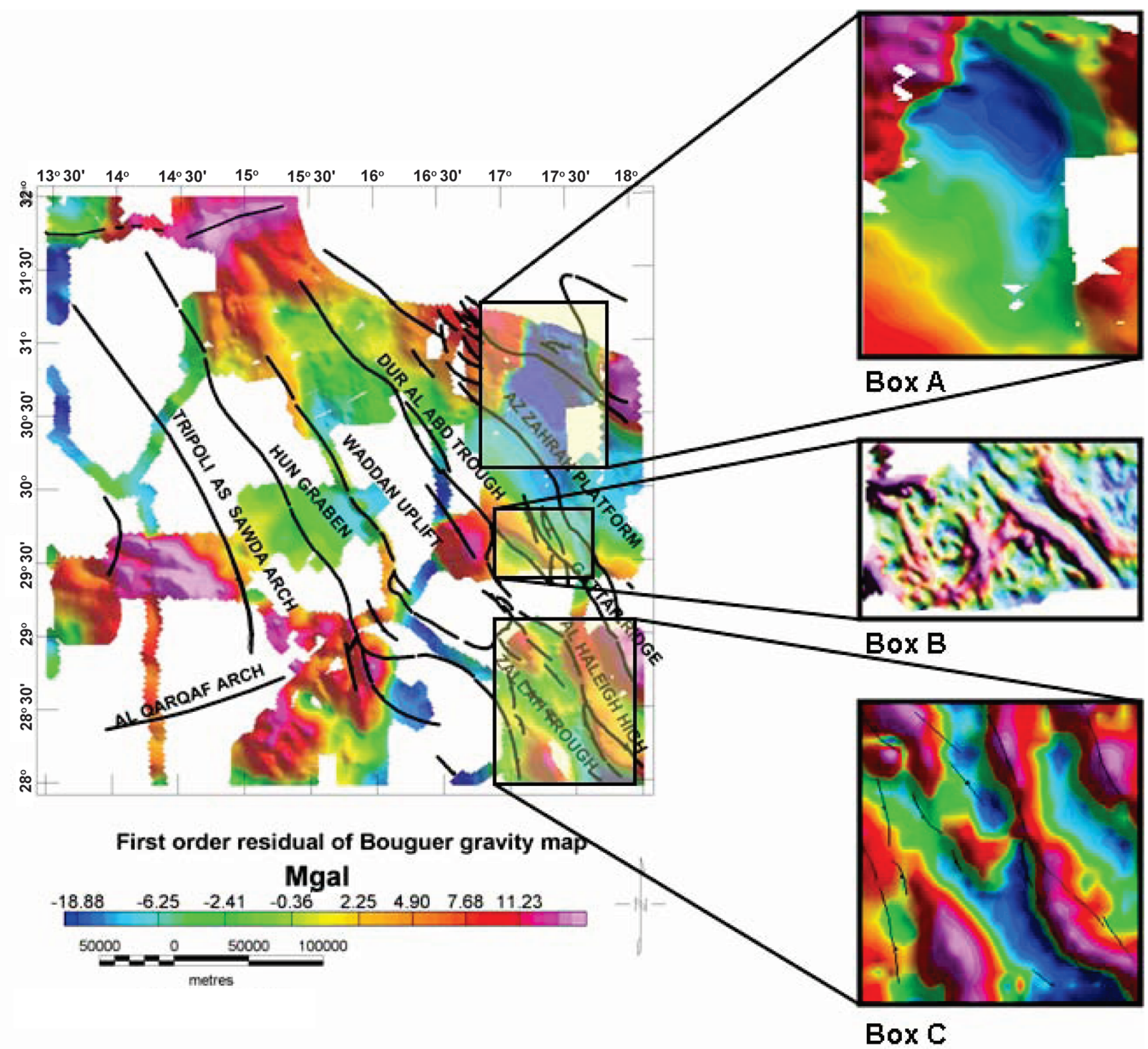

Fig. 6. First order residual Bouguer gravity map Box A shows a clear syncline to the north of Az Zahrah Platform, Box B is confirming the existence of a horst and graben to the southeast of Wadan Uplift and Box C reveals the clear boundries between Zallah rough, El Haleigh High and Gattar Ridge.

gradient belts into gradient maximum belts and further improves the resolution of faults, amplitudes which show the scale of the fault.

The tectonic trends become even more clear on the horizontal gradient map (Fig. 7). The gradient reveals the presence of several northeast-southwest trending anomalies that are not displayed on the tectonic elements maps. Among these anomalies, for example, is one that extends from the Mediterranean Sea and crosses the Az Zahrah Platform toward the southwestward direction of the study area. This anomaly appears to be displaced by the northwesterly trending structures (note the offset of the anomaly within the Az Zahrah Platform) and therefore associated with older geological events in the area.

CORRELATION BETWEEN SURFACE AND SUB-SURFACE STRUCTURES

The study area is characterised by a strong NNW-SSE structural grain which is consistent with the regional structure of the western Sirt Basin. The area has also been divided into a number of structural domains based solely on the surface structures expressed on satellite imagery (Fig. 3). The structural domains generally show good correlation with regional sub-surface structural features defined by seismic and potential field data.

Because of the variable coverage of the gravity data, it is not possible to carry out a complete interpretation of the gravity data. For the same reason, it is difficult to see if there is any correlation

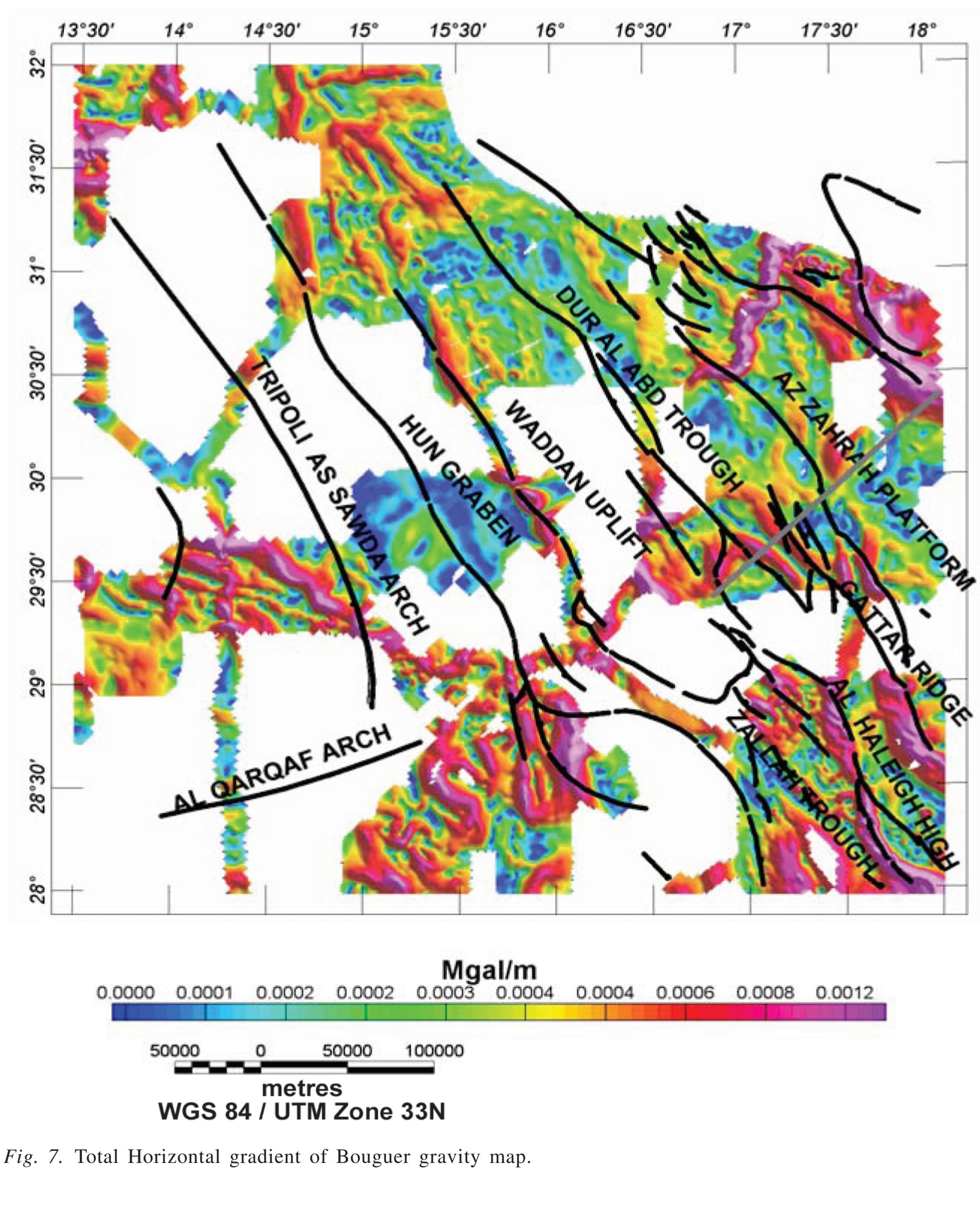

Fig. 7. Total Horizontal gradient of Bouguer gravity map.

between the Bouguer gravity data of the whole area (Fig. 6) and the tectonic elements trends and the geological structures (horsts and grabens). However, there is a good correlation at some places on the map (*e.g.*, Zallah Trough, Al Haleigh High, negative gravity anomaly within Az Zahrah Platform).

Hun Graben

It is a prominent Oligocene age structure bounded by steep cliffs which coincide with fault scarps or at least the eroded scarp slopes. It is not clear from the gravity data whether the graben affects the basement.

Az Zahrah Platform

The northern end of the Az Zahrah Platform (Fig. 4) is expressed at surface in the north by a homoclinal shallow NE dipping and marked by a NNW plunging nose of a large low-amplitude anticline. This anticline seems to be crosscut by a syncline (Fig. 6 Box A) located to the extreme northwest of it; its axis trends NE-SW and probably extending into offshore area. Several of the larger Az Zahrah Platform faults extend to the surface that revealed from satellite images are clearly observed on the seismic traverse as well.

Waddan Uplift

The W, S and SE boundaries are well-defined on the satellite imagery and bounded by normal faults down throwing to the W, S and SE respectively. The hinge zone between the Waddan Uplift and the Dur al Abd Trough contains many (about 8) large down-to-basin faults, two of which appear to extend to the surface. A graben linked to the SE part associated with NNW-SSE trending faults is confirmed by the gravity data (Fig. 6 Box B).

Zallah Trough

This is a well-defined structural domain on the satellite imagery characterised by low-lying relief, structural low region characterised by relatively smaller scale structures and preservation of Oligocene strata. Most of the major faults and broad low amplitude periclinal structures identified from the satellite imagery coincide with similar features obtained from the geophysical data.

The Al Haleigh High

It is defined as a basement high from satellite imagery by the outcrop of older stratigraphic units at the same structural level as younger strata. These areas are bounded on the both sides by faults that coincide with a gravity high (Fig. 6 Box C).

Dur al Abd Trough

Surface bed dips, combined with relatively thinner sedimentary sequence and relatively higher gravity values, indicate that the Dur al Abd Trough is shallower than the Zallah Trough.

EXPLORATION LEADS

A number of exploration leads have been identified in the study area (Fig. 4). They are primarily structural traps with a related surface expression as interpreted from the satellite imagery. The structural setting of existing oil fields in the region were used as analogues for assessing the exploration potential of the surface structures. The following exploration leads have been identified:

- Surface four-way closure (low amplitude periclinal structures) at the southern end of the Waddan Uplif. The structure is along strike from surface closures associated with the Al Haleigh High and the Karim, Aswad and Zallah oil fields.
- Down-faulted trap-door type structure located at the southeastern side of the Waddan Uplift. The structure is dependent on the western bounding fault to be a sealing fault. Migration would be up-dip from the Zallah Trough.
- The western margin or crest of the northeast tilted Gattar Ridge where the Palaeocene carbonates are likely to be highly fractured due to the proximity of the western boundary fault. Due to the amount of downthrow across the Az Zahrah Platform bounding fault to the east, the structure would probably require oil migration from the Zallah Trough.
- Northern end of the Hun Graben. This lead depends on there being a complex structural trap involving the interaction of gentle northeast dipping strata, NNW-SSE boundary faults of the Hun Graben and the ENE-WSW trending fault zone. The prospectivity of this area is dependent on oil generation and migration from the Zamzam Depression, and there being suitable reservoir(s).

• NNW-SSE trending fault zone in the western part of the study area. The fault may provide a structural trap at the eastern margin of the Ghadamis Basin.

CONCLUSIONS

The present study shows a good correlation between surface and subsurface structure defined by seismic and potential fields data. The study area is dominated by a NNW-SSE structural grain related to Cretaceous extensional tectonics and possible influence of pre-existing Pan-African basement structure.

Major ENE-WSW trending structures appear to be superimposed on the NNW-SSE structures. This trend may be influenced by pre-existing Hercynian structure. ENE-WSW structures may have a greater influence of the productivity of the structural traps generally attributed to the NNW-SSE trend.

Preservation of Mazul Ninah and late Tertiary-Quaternary deposits within structural and geomorphological depressions indicates that subsidence is ongoing along the eastern margin of the Zallah Trough and possibly within the Hun Graben.

The study area can be divided into twelve structural domains consisting of the Zallah, Dur al Abd, Hun Graben, Ghadamis and Zamzam Depression; the Waddan uplift, Gattar Ridge, and Az Zahrah Platform; the Nafusah Uplift and Al Qarqaf Arch; the Tripoli-As Sawda Uplift and the intrabasinal Al Haleigh High.

The main structural traps are:

• The crests of major NNW-SSE trending northeast tilted fault blocks developed along the basin margins e.g. Az Zahrah Platform and Gattar Ridge.

• Four-way periclinal fold closures developed as drape structures and/or drape structures related to differential compaction above smaller scale intrabasinal basinal highs such as the northern extension of the Al Haleigh High.

Six exploration leads have been identified, although the main prospective areas are within the Zallah Trough itself and the up-dip crests of adjacent platforms.

The Hun Graben appears to be an Oligocene age structure, which is probably unprospective due to the lack of reservoir and source rocks.

Western Hun Graben structure is generally characterised by a gentle northeast dipping homoclinal panel with no surface expression of any structural trap. Migration would tend to be towards the southwest. Possible seepage may occur along faults associated with the NNW-SSE trending fault zone or further west in the true structural crest of the Tripoli-As Sawda Uplift and adjacent margins of the Ghadamis Basin.

The flank of the western Sirt Basin may be defined by the Hun Graben. However, this structure is only Oligocene and the western limit of the Sirt Basin most likely extends to the west of the Hun Graben, possibly to the eastern edge of the Tripoli-As Sawda Uplift.

ACKNOWLEDGEMENTS

We wish to extend our thanks to Dr Martin Insely of Infoterra, (UK) for his supervision and without him, this paper would not have been possible. We also appreciate the approval and support from the management of the Libyan Petroleum Institute, (Libya) to publish this paper.

REFERENCES

Ahlbrandt, T.S., 2001, The Sirte Basin province of Libya – Sirte-Zelton total petroleum system, *U.S. Geological Survey Bulletin* 2202-F, 29p.

Anketell, J.M. 1996. Structural history of the Sirt Basin and its relationship to Sabratah Basin and Cyrenaican Platform, northern Libya. In: M. J. Salem, M. T. Busrewil, A.A. Misallati, and M.A. Sola (eds). *The Geology of the Sirt Basin*, Elsevier, Amsterdam, **III,** 57-89.

El-Batroukh, S.I., and Zentani, A.S., 1980, Gravity interpretation of Raguba field, Sirte basin, Libya. *Geophysics*, **45**, 1153-1163.

Klitzsch, E. 1971. The structural development of parts of north Africa since Cambrian time. In: C. Gray (ed). *First Symposium on the Geology of Libya* Faculty of Science, University of Libya, Tripoli, 253-262.

Mijalkovic, N. 1977. Geological Map of Libya, Sheet Al Qaddahiyah (NH 33-3), scale 1:250,000, Explanatory Booklet, Industrial Research Centre, Tripoli. 66p.

Morelli, C., Cantar, C., Honkasalo, T., McConnell, R.K., Tanner, J.G., Szabo, B., Uotila, U., and Whalen, C.T., 1974. The international gravity standardization net 1971 (IGSN71). *Int. Assoc. Geod., Spec*. Publ. 4.

Said, M. 1981. Geological Map of Libya, Sheet Bunjim (NH 33-7), scale 1:250,000, Explanatory Booklet, Industrial Research Centre, Tripoli, 92p.

Zivanovic, M. 1977. Geological Map of Libya, Sheet Bani Walid (NH 33-2), scale 1:250,000, Explanatory Booklet, Industrial Research Centre, Tripoli, 71p.